FURTHER RESEARCHES ON THE PHYSICS OF THE EARTH, AND ESPECIALLY ON THE FOLDING OF MOUNTAIN RANGES AND THE UPLIFT OF PLATEAUS AND CONTINENTS PRODUCED BY MOVEMENTS OF LAVA BENEATH THE CRUST ARISING FROM THE SECULAR LEAKAGE OF THE OCEAN BOTTOMS.

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I. General Considerations on the Physics of the Earth, with Especial Reference to the Secular Leakage of the Oceans and the Resulting Development of Mountains, Plateaus and Islands.

§ 1. *Introductory Remarks.*—In three papers recently communicated to the American Philosophical Society held at Philadelphia and since published in the proceedings of that Society,[1] the writer has treated at some length of the cause of earthquakes, moun-

[1] 1. "The Cause of Earthquakes, Mountain Formation and kindred phenomena connected with the Physics of the Earth," Proc. Am. Philos. Soc., 1906.

2. "On the Temperature, Secular Cooling and Contraction of the Earth, and on the Theory of Earthquakes held by the Ancients," Proc. Am. Philos. Soc., 1907.

3. "The New Theory of Earthquakes and Mountain Formation as illustrated by Processes now at work in the Depths of the Sea," Proc. Am. Philos. Soc., 1907; issued in March, 1908.

The following shorter articles have also appeared:

4. "Outline of the New Theory of Earthquakes," *Popular Astronomy*, April, 1908.

5. "How the Mountains were Made in the Depths of the Sea," *Pacific Monthly*, Sept., 1908.

tain formation and kindred phenomena connected with the physics of the earth. In the course of these three memoirs many important questions are considered, and it seems to be rendered highly probable that six great classes of phenomena, not heretofore closely associated, depend on a single physical cause, namely, the secular leakage of the ocean bottoms, and the resulting movement of molten rock beneath the earth's crust. The six classes of phenomena traced to a single physical cause are: (1) world-shaking earthquakes; (2) the activity of volcanoes; (3) mountain formation; (4) the formation of islands and plateaus; (5) seismic sea waves; (6) the feeble attraction of mountains and plateaus long noticed in geodesy.

The first of the memoirs printed by the American Philosophical Society deals with the problem of earthquakes in its general aspects, and sets forth grounds for the theory that these six classes of phenomena are directly connected and dependent on a single physical cause; the second examines the question of the earth's temperature, secular cooling and contraction, and endeavors to show that the traditional theory of the changes noticed on the earth's surface is not well founded; while the third seeks to demonstrate the more important conclusions reached in the first memoir, by an appeal to processes now at work in the depths of the sea, the meaning of which apparently is so plain as to admit of no possible doubt.

The change in the point of view necessitated by the considerations brought forth in these papers is so remarkable as to be worthy of the attention of all who are interested in the grand science of natural philosophy. And we therefore propose to consider in this paper the physical basis of the theory of ocean leakage, the folding of mountain ranges and the uplift of plateaus and continents produced by movements of lava beneath the crust, together with the historical aspects of the problems of the physics of the earth. Heretofore the nature of the forces which have folded mountain ranges and their relationship to those slow movements which have raised whole continents have been equally mysterious and bewildering to the investigator. Accordingly any light which may be shed on this difficult subject will no doubt be exceedingly welcome to those who are interested in the progress of the physical sciences.

As the leakage of the oceans seems to be clearly proved by the movements noticed in earthquakes, especially where mountain formation is now going on in the depths of the sea, and the seismic disturbances are therefore accompanied by the sinking of the sea bottom, as shown by the seismic sea waves which follow the earthquakes, it seems legitimate to appeal to these movements of molten matter beneath the earth's crust as the only available means of demonstrating the porosity and other physical properties of layers of granite twenty miles thick. Owing to the restricted conditions of human life, no experiments on such a grand scale can ever be attempted in our laboratories, however great the facilities at our command; and our only means of ascertaining the truth with regard to the theory of ocean leakage is by careful observation in the great laboratory of nature. The leakage of the oceans involves three important questions: (1) The porosity of thick layers of matter such as those composing the earth's crust; (2) the penetrability of the crust under steady fluid pressure, by which the capillary forces are made to aid the molecular forces producing penetration of the fluid; and (3) the accumulation of stresses depending on the formation of steam in the layers just beneath the earth's crust.

The conditions existing in nature can scarcely be approximated in our laboratories, on account of the limitations of the forces at our command, but so far as experiments throw light on these great questions, the evidence tends to confirm the theory of ocean leakage. The well-known experiments of Daubrée, showing that under the action of capillary forces hot water will penetrate a layer of sandstone against a strong counter pressure of steam, and by entering a cavity actually increase the steam pressure on the further side, has been justly held to afford evidence of the leakage of the earth's crust, and of the probable mode of volcanic activity. If such action is possible in a minute way, it may easily operate on a vastly greater scale to produce the shaking of the crust in earthquakes, together with the uplift of mountains and the occasional outbreak of volcanoes.

Now if the rock of the earth's crust is at all as porous as we generally think, the constant pressure of the vertical column of water, often miles deep, resting on the ocean bed must tend to force the fluid deeper and deeper into the bowels of the earth. A study of what takes place on our earth under the observed conditions constitutes therefore one of the grandest problems in natural philosophy.

Indeed it may be said that the great laboratory of nature has magnificent experiments constantly going on. All that we need to do is to interpret these experiments correctly. The best way to do this is to select phenomena in which the processes are so clear as to be free from doubt; after we have found the law of the phenomena in cases which are beyond question, we may then generalize and interpret other phenomena, in which the relations are not so obvious. By gathering principles and laws from cases which are entirely clear, and working by degrees to understand those which are more obscure, we may finally arrive at the true processes even when the operations of nature are quite hidden from our view.

Laws thus established by observation in the great laboratory of nature will obviously hold true of like experiments in the minute physical laboratories designed by man; and by noting the phenomena of the globe we may extend our knowledge of the universal properties of matter under various physical conditions often more extreme than those ordinarily witnessed at the surface of the earth.

§ 2. *Heretofore the ocean bottoms have been assumed to be water-tight.*—The earth's crust is made up chiefly of sedimentary, igneous and granitic rocks, and soil produced by the decomposition of the various kinds of rock under the action of water and the atmosphere. Nearly all of the sedimentary rocks are quite leaky, and moreover they absorb a great deal of moisture from the air; the formation of artesian wells and of natural springs depends primarily upon the percolation of water through rocks and layers of soil of various kinds. The leaky character of the sedimentary rocks is well known and has been generally recognized. But these rocks exist only near the surface, and do not extend more than a very few miles deep; consequently they could admit the water to but a slight depth into the earth's interior. Below the sedimentary rocks lies the mass of granite which makes up by far the greater part of the earth's crust. The granitic rocks, such as granite, andesite, diabase, etc., are by no means so penetrable as the sedimentary rocks, and hence water has more difficulty in passing through them. And as the layers of this material composing the earth's crust are about fifteen miles deep, it has been generally held that water would have difficulty in making its way down into the heated layers just beneath the crust.[1] Indeed it has been practically assumed that the ocean bottoms are water-tight, in spite of the great fluid pressure constantly exerted by the mere depths of the water over a large part of the bottom of the sea. This fluid pressure in many places is great enough to throw a column of water to the free surface, over five miles high; and it operates not only from day to day, year to year, but also from century to century, age to age. If granite is at all penetrable by water, is it therefore any wonder that a gradual secular leakage should go on, and at length, by a kind of slow perspiration of the stone, give rise to sufficient accumulation of steam beneath the crust to produce a swelling of the saturated mass, and require a readjustment of the overlying rocks?

Now it happens that by nature all the granitic rocks are crystalline, and thus somewhat coarse-grained in structure; so that they absorb water from the ground and moisture from the air. The crystalline structure permits penetrability to a greater degree than would fine-grained and very hard rocks such as agate; but no rock has such fine pores as the metals, and especially vitreous bodies like glass, to which agate is an approximation. And as all the metals are proved by experiment to be leaky under great fluid pressure, and glass is shown to obey the same law, it obviously follows that all rocks are leaky under great fluid pressure. Consequently under the incessant pressure of the oceans water must make its way into the heated layer just beneath the earth's crust.

Heretofore the possibility of earthquakes cracking the ocean bottom has been generally recognized, but it has been held that

[1] This statement is perhaps too positive, for Sir William Ramsay, the celebrated British Chemist and Physicist, writes me that he has long believed that the ocean bottom leaks and that the formation of minerals takes place chiefly in the bed of the sea. Undoubtedly this view will come to be generally accepted. Similar views seem to be held by Lord Rayleigh, Sir Wm. Huggins, Arrhenius and many other eminent physicists.

crevices thus formed would not extend over five or six miles deep before they would be closed by the effects of pressure, which naturally increases rapidly as we descend into the earth. The belief has therefore prevailed that although the bed of the sea might be rent by an earthquake, it would immediately close up again, and water would thus be prevented from entering the bowels of the globe.

It scarcely seems to have occurred to investigators to consider the effects of the constant hydrostatic pressure resulting from the depth of the sea, in forcing the water slowly through the fifteen miles of granite composing the earth's crust. A crevice is small, and would let in but little water when closed up quickly; but the whole sea bottom is large, and unless it is really water-tight, even a slow leakage over a large area would at length develop stresses beneath which would necessitate a readjustment of the overlying blocks of the crust. This readjustment is ordinarily called an earthquake.

Moreover the great abundance of submarine earthquakes has been largely overlooked by previous investigators. It is the secular effect of the constant pressure of the oceans and of capillary forces in promoting the downward movement of the water which has been generally lost sight of.

But if we admit on the basis of experimental evidence that water can penetrate thin layers of granite, the question naturally arises: Can it also penetrate a layer of granite fifteen or twenty miles thick? It seems obvious that it can, because for small or moderate pressures water is nearly incompressible and would not sensibly increase in density as it went down into the globe. The fluid which passed through the upper layer of granite would therefore keep on descending, under the increasing fluid pressure from above, and at length the whole layer would be saturated, and perspiring below with a steady leakage which would give rise to tremendous steam power in the underlying molten rock. Thus great stresses due to slow accumulation of steam would develop in the layer just beneath the crust, and this would give rise to earthquakes and mountain formation.

Among the practical men of science to whom the problem of ocean leakage was submitted, we might name some of the most

eminent of living physicists. While disclaiming especial authority to pass upon such a question, they expressed the opinion that it was very improbable that the ocean bottom could be water-tight, unless the nature of the rock was greatly modified by pressure, which could hardly be the case in the first twenty miles of the earth's crust, where the pressure does not exceed 8,600 atmospheres.

Whatever doubt might attach to this solution of the problem, from an experimental standpoint, where positive knowledge is greatly lacking, seems to be dispelled by the phenomena noticed in the sea bottom in various places, which show that lava is expelled from beneath the sea and pushed under the adjacent land. The phenomena noticed in the laboratory of nature thus prove the leakage of the ocean from an observational standpoint, because they admit of no other interpretation.

§ 3. *The Theory of Water-tightness of the Ocean Bottoms Disproved by the Expulsion of Lava from under the Sea.*—Just south of the Aleutian Islands, a long, narrow and deep trench just parallel to this chain has been dug out by the expulsion of lava from beneath the sea. The nature of this trough is illustrated by the accompanying Map.

It will be seen that the island chain adjacent to the trough dug out in the sea bottom is really a mountain range under water, with only occasional peaks projecting above the water as islands. In fact the Aleutian Islands are a continuation of the Alaskan Mountains which are part of the Rocky Mountain System, and the range here continues into the sea. If therefore the Aleutian Islands are mountains now in process of formation in the sea, it would seem to follow logically that the Rocky Mountains and Andes, from Alaska to the straits of Magellan, were formed in the same way. What then is the process at work forming the Aleutian Islands?

It is evident that the deep trench south of the islands has been dug out by the expulsion of lava from under the sea and its injection under the Aleutian ridge; this is accomplished by earthquakes, and the process is still in full operation at the present time. This region is a well-known breeding-ground for world-shaking earthquakes and seismic sea waves. Several islands have been uplifted since 1783, and one or more new volcanoes have broken out within the historical period. The seismic sea waves following the earthquakes which affect this region indicate that the sea bottom often sinks after these disturbances. In other words, when lava is expelled from under the trench and pushed under the adjacent ridge, the bottom gives down to secure stability. The processes now going on have been at work through immense ages, and have thus dug out the trough parallel to the Aleutian Islands, and at the same time elevated this ridge, till it is now partly above the water, thus constituting the chain of islands.

In like manner the great earthquake at Yakutat Bay, farther east, September 3–20, 1899, which was so carefully investigated by Tarr and Martin (*Bulletin of the Geological Society of America*, May, 1906) raised the coast for about 100 miles; the maximum elevation being 47⅓ feet. Subsidence also occurred in a few places. Such a vast movement of the coast indicates an enormous expulsion of molten rock from beneath the sea under the land. It is these subterranean movements beneath the earth's crust which shake down cities and devastate whole countries. During the earthquake at Yakutat Bay the shaking was so terrible that persons could not stand on their feet; avalanches slid down the mountains, and glaciers were carried into the sea. This is the true nature of earthquakes, and one need not therefore be surprised at the devastation produced. The force which pushes lava under the land, overcoming the weight of the crust, naturally destroys cities and all the frail works of man built upon the surface.

§ 4. *Physical Experiments on the Porosity of Matter.*—Modern science presents many illustrations of the *porosity* of matter. In fact so many experiments illustrate *porosity* that it is difficult to find proof of the general property of *impenetrability* cited by Newton in the "Principia," except under the narrow limitations that the matter in question remains cold and the forces to which it is subjected are small. With increasing fluid pressure and rising temperature all matter is leaky; and in general a rise of temperature expands and thus augments the penetrability and porosity of all substances. *We may therefore say that all matter is porous and leaky under great fluid pressure, and impenetrability does not exist except* *under very restricted conditions, so that it is not a general property of matter as was once supposed.*

In the early days of physical science the demonstration of the porosity of such dense bodies as gold, silver and lead was considered a great achievement. In 1661 some academicians at Florence, repeating an earlier experiment of Bacon with a spherical shell of lead, filled a hollow sphere of solid gold with water, and, after sealing it hermetically, flattened the figure of the spherical shell in a hydrostatic press so as to diminish the volume. Under this deformation of the sphere the water was forced through the walls of solid gold and formed in drops on the outside. Corresponding experiments were made with spheres of silver, lead, and other metals, with analogous results. Modern engineering presents innumerable illustrations of the porosity and leaky character of structures made of the hardest bodies. Under great pressure all pipes and pistons leak, and put a limit to the applications of hydrostatic pressure.

In 1883 Amagat forced mercury through plates of solid steel three inches thick, under a pressure of about 4,000 atmospheres. This is the highest pressure hitherto applied in physical experiments, and yet all rocks are subjected to such pressure at a depth of only ten miles below the earth's surface. In the measurement of ocean depths it has been found that empty hollow glass balls with walls half an inch thick sent down with the deep sea apparatus come up more and more completely filled with water, according to the depth of the sea and the duration of the experiment. As glass is the most impervious of solid bodies, this leakage, which it shows under the external application of fluid pressure from the deep sea, is a good illustration of what happens to the bed of the ocean, which is constantly subjected to this pressure. No rock is anything like so impervious as glass, and consequently a general leakage of the ocean bottom inevitably takes place. The water which first enters the bed of the sea will keep on descending till it comes into contact with rock at high temperature, which produces and readily absorbs steam. When the rock becomes saturated with steam it swells and requires more space, and this finally brings on an earthquake. Hence also the preponderance of great earthquakes under the sea and the almost total absence of these disturbances far inland.

§ 5. *Important Criterion for the Nature of the Movement Beneath the Earth's Crust furnished by Seismic Sea Waves.*—In the paper on the "Cause of Earthquakes" we divided seismic sea waves into two general classes: the first, due to the sinking of the sea bottom, and characterized by a withdrawal of the water after the earthquake, to be followed later by the return of a great wave; the second, due to the uplift of the bottom, and characterized by the sudden rise of the sea without any previous withdrawal from the shore. Both classes of these waves exist in our seas, but those of the first class are the most dangerous and the most important. Most of the great historical inundations by the sea have been due to waves of the first class. The phenomena usually noted are: first, a terrible earthquake; second, after a short interval, the sea is noticed to be slowly draining away, laying bare the bottom, where it ordinarily is deep enough to anchor ships; third, after an interval of an hour or so, the sea is seen to be returning as a mighty wave, carrying everything before it, and thus washing the ships inland and stranding them high and dry; fourth, having once swept the shore, the sea again withdraws and lays bare the harbor as before, and after about the same interval again returns as a second great wave. This periodic movement of the sea may be kept up for quite a while, and sometimes quiet is not restored for a day or two.

Among the many well-known historical sea waves of the first class which might be mentioned, we shall cite only a few typical cases: As that which overwhelmed Helike in 373 B. C. (see the paper on the "Temperature of the Earth," § 23, pp. 269–272, and Addendum, pp. 291–298); the wave at Callao in 1746; the wave following the Lisbon earthquake in 1755; the waves of Arica, 1868, and Iquique, 1877; the wave on the Japanese coast in 1896. In all these cases the water first withdrew from the shore; not suddenly, but slowly, as in the draining away of a tide, though somewhat more rapidly; this of course indicated that the sea bottom had sunk, and the water was draining away to fill up the depression in the level caused by the drop of the bottom. When the currents meet at the center an elevation is produced by their mutual impact, and when this collapses under gravity the first great wave comes ashore. The elevation then subsides into a depression as at first, and the currents again flow in and force up the level a second time; and with the second collapse another wave is sent ashore; and so the oscillation of the sea continues, sometimes for a day or two before it finally quiets down.

Now these sea waves of the first class furnish an exceedingly important criterion as to the nature of what is going on beneath the earth's crust. The sinking of the sea bottom often happens in the deep trench south of the Aleutian Islands, and repeated drops of this kind have obviously produced the deep trough parallel to these islands. For it is observed that the earthquake usually raises one or more of the islands to the north, when the sea bottom sinks to the south. Now the islands could not be upraised unless something was pushed under them, and the bed of the trough could not sink down unless it was in some way undermined. Accordingly it follows that molten rock is expelled from beneath the bed of the trough to the south and pushed under the adjacent islands to the north, which are thus uplifted. The bed of the sea often sinks during the earthquake arising from this subterranean movement, and then the water withdraws from the shore and afterwards returns as a great seismic sea wave. It will be observed that the subcrustal movement is from the sea towards the land, because steam accumulates under the ocean, but scarcely at all under the land.

Thus these seismic sea waves become very important criteria for determining whether the sea bottom has sunk; and if it has sunk we know that lava was expelled from under the sea and pushed under the land. Seismic sea waves therefore may be regarded as *very delicate levels,* for determining the movement of the sea bottom; and from the nature of this movement we can often decide what the effect of the earthquake has been. Moreover these waves enable us to tell with certainty that the chief function of earthquakes is the elevation of the land along the coast by the expulsion of lava from beneath the bed of the sea. It is not too much to say that the true nature of earthquakes and their function in the uplift of mountains and plateaus could not be certainly made out except for the exceedingly important criterion furnished by seismic sea waves.

§ 6. *Additional Phenomena Noticed near the Aleutian, Kurile and Japanese Islands, and the Antandes.*—South of the Aleutian chain, as just remarked, a well-known earthquake belt parallels these islands, and the seismic disturbances occurring there are frequently followed by seismic sea waves of the first class. Soon after a great earthquake the water is seen to be withdrawing from the shore, and after a short interval of time it again returns as a mighty wave sweeping everything before it. Many volcanoes have broken out in these islands and several new islands have been uplifted within the historical period. The Russians long ago connected the earthquakes with the volcanoes in the Aleutian Islands. In later years the exact survey of the sea bottom has shown that it is sunk down into a narrow trough right under the earthquake belt. Just parallel to the trough the islands form a real mountain ridge under water, with only a few of the highest points projecting above the surface as islands. The uplift of these islands therefore denotes the uplift of mountain peaks, some of which have become volcanoes.

Now if the earthquakes are accompanied by the uplift of islands and the sinking of the sea bottom, as shown by the seismic sea waves, it follows that the uplift of the ridge is connected with the sinking of the adjacent sea bottom. As the ridge is just contiguous to the trench, and the earth is terribly shaken every time these disturbances occur, it seems to indicate that matter is expelled from under the trench and pushed under the ridge; so that the ridge is elevated and the trench sinks down correspondingly. This could not occur without the bodily transfer of matter beneath the earth's crust, and the shaking of the earth is due to this expulsion of lava from under the trench, and its injection under the ridge. This is the only possible explanation of the observed elevation of the ridge and the sinking of the trench. In this way the trough near the Aleutian Islands has been gradually dug out. Similar troughs have been formed by earthquakes near the Kurile and Japanese Islands, as we know by the observed depth of the sea, the lay of the earthquake belt parallel to these islands, and the occurrence of the seismic sea waves, showing that the sea bottom sinks after the earthquakes by which the region is afflicted. If the islands of Japan were dug off and thrown into the Tuscarora Deep, they would about fill it up.

Therefore all these islands were formed by the expulsion of lava from under the sea, and the subsequent sinking of the sea bottom has given rise to the deep troughs now found in that part of the ocean.

In the same way there is an earthquake belt between Samoa and New Zealand, and the sea bottom is sunk down into a deep trough, parallel to a ridge on the west, on the opposite side of the trench from the ocean. This ridge is a new mountain range 1,200 to 1,500 miles long, now forming on the west of the Pacific, just as the Andes were once formed on the east. Lava is being expelled from under the trench and pushed from the ocean towards the ridge on the west. This is developing into a new mountain range, which we shall call the *Antandes,* because it is being formed opposite to the Andes, on the other side of the Pacific, and in the same manner as the mighty mountains in South America were in earlier geological time. In the course of immense ages the Antandes will rise above the water as a mighty chain on the west of the Pacific just like the Andes on the east.

These phenomena in the sea bottom show the real process of mountain formation at various stages of its progress, and prove to us that most of the folding observed in our mountain ranges now on land really took place in the bed of the sea, long before the whole range was raised above the water. For this sinking and upheaval of adjacent portions of the sea bottom would crumple the rocks exactly as they are observed to be in all mountain ranges; and moreover the several parallel ranges so often observed would result from the development of several parallel troughs, all of which are eventually uplifted. It will be observed that the expulsion of lava is always from the sea towards the land, and this shows that the sole cause of the movement is the leakage of the ocean. It thus follows that mountains, plateaus, and islands are uplifted by earthquakes depending on the leakage of the oceans, and by nothing else.

§ 7. *The Andes with their high Plateaus Merely a Vast Wall Erected by the Pacific.*—It may sound strange to say that the cordillera of the Andes is a vast wall erected by the Pacific Ocean along its border; but to the navigator who traverses the shore from Panama to Cape Horn such a description will seem most appropriate.

FIG. 1. Relief Map of South America. (From Frye's Complete Geography, by permission of Ginn & Co., Publishers.) Notice that the Andes are a mighty wall erected by the Pacific Ocean along its border. Professor Charles Burkhalter, Director of the Chabot Observatory, Oakland, kindly suggested the use of these relief maps, which are well suited for bringing out the leading characteristics of the different continents.

Throughout the length of the continent the mountains are everywhere parallel to the coast, and run at nearly a constant distance from the shore. The Andes are not always a simple chain, but they are narrow relatively to their height, as compared to the other mountains. In many places there are two or more ranges with narrow plateaus between. These plateaus are so interwoven with the mountains themselves that we may feel sure they were formed together and represent a part of one general movement. Unless this were so it is impossible to believe that so many narrow and high plateaus would be enclosed between mountain walls on either side. The eastern cordillera is less volcanic than the western, and the eastern slope is believed by Professor Solon I. Bailey of Harvard College Observatory, who has exceptional opportunities for judging of these mountains, to be two or three times steeper than the western slope.

If we suppose a sea trough was first dug out in the elevation of the eastern range, and eventually when deep sediments had accumulated in the trough, the western edge of it was folded up to form the western range, and the trough itself became the plateaus, we shall have very nearly a true picture of how the Andes were formed. The full details of this process cannot be given now, but there is no doubt that the Andes are a vast wall erected by the Pacific along the edge of the continent. This origin of these mountains is also indicated by the earthquakes observed within historical time; for the coast has been again and again upraised by these disturbances, while the sinking of the sea bottom, indicated by the accompanying seismic sea waves, shows that the bed of the ocean is being undermined by the expulsion of lava under the land. The shells, fossils, and other evidences of marine life now found at altitudes as high as 15,000 feet show that the uplifting at present going on is but a part of the greater uplift of past geological ages; so that the great movement which formed these mountains and plateaus is identical with the earthquake disturbances noticed within historical time.

§ 8. *The uplift of mountains and plateaus around the margins of the Pacific, and of islands in the interior, with innumerable submarine eruptions everywhere, is nature's way of indicating leakage* *through twenty miles of crust.*—The peculiar position of the sea bottom between a molten globe and the overlying ocean is such that any disturbance of the bottom, as in a volcanic eruption, would naturally excite our suspicions that the crust had leaked and brought the water into contact with the underlying ball of fire. The situation of the overlying ocean, with the fire so close beneath, is much the same as that of the water above the furnace of a boiler, in which steam is developed; and if one had the molten globe for a furnace and the ocean for a reservoir of water, leakage would develop steam on a grand scale, and give rise to mighty experiments exactly resembling earthquakes and volcanic eruptions. Some of these disturbances might take the form of uplifts of the crust into islands, mountains and submarine volcanoes, others near the edges of the sea would cause lava to push out under the land and raise the coasts.

Now the Pacific Ocean is everywhere surrounded by high mountains, as if the lava had been pushing out at the margins of the sea. And throughout the interior a vast number of islands are raised up in deep water, and every part of the ocean is from time to time disturbed by terrible earthquakes. One must therefore admit that the ocean has the aspect which might be expected to result from a leakage of the ocean bed. Moreover the Pacific is surrounded nearly everywhere by volcanoes, which emit chiefly vapor of steam. If it is shown that mountains are formed by earthquakes, chiefly in the expulsion of lava under the land, and some of the mountains break out into volcanoes, then there will obviously be a connection not only between earthquakes and volcanoes, but also between the vapor of steam emitted from these smoking mountains and that formed under the ocean by the leakage of the bottom.

It is this intimate connection between all the related phenomena which tells so powerfully in favor of the view that the leakage of the ocean takes place through a layer of rock twenty miles thick. The height of the mountains and plateaus is but a small fraction of the thickness of the crust, and movement in the underlying layers therefore usually gets relief without breaking through. The crust of the globe is thick enough to offer great resistance to uplift, so that the steam saturated lava usually adjusts itself beneath without a surface eruption. Yet where the crust is sharply upheaved as in mountains, volcanoes sometimes break out. But it is obvious that earthquakes are the more general, volcanoes the more special phenomena; and that both are connected with mountain formation, and depend on the sea for their continued activity.

§ 9. *On the Structure of Granite as a Typical Crystalline Rock of the Earth's Crust.*—Granite has a thoroughly crystalline structure, and is an admixture of feldspar, mica, and quartz. The mica is in the form of minute shingles, or snowflakes, embedded in the noncrystalline matrix of quartz, which encloses the other elements. The feldspar is chiefly orthoclase. The two chief ingredients, quartz and feldspar, form a granular aggregate made up of grains of fairly equal size, varying all the way from several inches in diameter to a structure so fine as to be inseparable to the naked eye.

"Many granites contain irregularly shaped cavities (miarolitic structure), in which the component minerals have had room to crystallize in their proper forms, and where beautifully terminated crystals of quartz and felspar may be observed. It is in these places also that the accessory minerals (beryl, topaz, tourmaline, garnet, orthite, zircon and many others) are found in their best forms. Not improbably these cavities were somewhat analogous to the steam holes of amygdaloids, but were filled with water or vapour of water at high temperature and under great pressure, so that the constituents could crystallise under the most favorable conditions. Among the component minerals of granite, the quartz presents a special interest under the microscope. It is often found to be full of cavities containing liquid, sometimes in such numbers as to amount to a thousand millions in a cubic inch and to give a milky turbid aspect to the mineral. The liquid in these cavities appears usually to be water, either pure or containing saline solutions, sometimes liquid carbon-dioxide" (p. 143). (Sir A. Geikie, "Geology," p. 204.)

The cavities in crystalline rock such as granite may contain either gas or liquid matter, and sometimes both. Professor Tilden's researches have shown that the included gases (hydrogen, carbon dioxide, carbon monoxide, marsh gas, nitrogen, and water vapor) may exceed many times the volume of the rock itself. The cavities have all manner of forms, branching, oblong, curved, oval, spherical and negative crystalline shapes, and are often so numerous as to give a turbid aspect to the mineral. The intersecting planes of the crystalline granite frequently present real fissures more or less filled with liquid. Obviously capillary forces may here attain great importance, and fluid entering the rock would be absorbed into these spaces with irresistible power. Geikie remarks that the cavities in quartz have all sizes from the coarse pores visible to the naked eye to minute spaces less than 1/10,000 of an inch in diameter, which can be seen only under high magnifying power.

Now it is worth while to remember that small as are the least cavities and fissures which we can see with the microscope, they are very large and coarse compared to the molecular structure of a fluid such as water or of a solid like glass. It is useful to remember that the limit of naked eye vision is about 1/250 of an inch, and of the most powerful microscope about 1/100,000 of an inch. The microscope therefore increases our power of vision about 400 times. (Cf. Prof. A. A. Michelson's "Light Waves and their Uses," p. 30.)

§ 10. *On Lord Kelvin's Determination of the Size of Atoms.*—In order to form a clear conception of the physical constitution of the matter composing the crust of the globe, we must recall the lines of research by which Lord Kelvin has determined the size of atoms.

1. By determining the work done or heat produced in bringing thin plates of zinc and copper together. The observed amount of heat evolved when the plates are made of given thickness and afterwards imagined to be thinner and thinner, limited only by the condition that the mass shall not be melted, under the heat of combination, which is not indefinitely great even when brass is produced by fusing zinc and copper, but corresponds to the mutual attraction of a number of plates not more numerous than 100,000,000 to the millimeter; hence it follows that the molecules are at least 1/1,000,000,000 cm. and probably more than 1/400,000,000 cm. in diameter. Lord Kelvin concluded that "Plates of zinc and copper 1/300,000,000 of a centimeter thick, placed close together alternately, form a near approximation to a chemical combination if indeed such thin plates could be made without splitting atoms." He fixed 1/1,000,000,000 of a centimeter as the minimum diameter of the atoms found in this way. It is to be remembered here that 2.54 centimeters = 1 inch.

2. By the study of Newton's rings on soap bubbles as they become thinner and thinner, the thickness of the film being reckoned from the known wave-length of the reflected light. Unless the film materially weakened when a certain limit is attained, it could not be stretched beyond a certain thickness without volatilizing, if

maintained at the same temperature; for as it expands it cools, and the heat that would have to be supplied to it would be more than sufficient to vaporize it. Now it is found by observation that the intensity of the surface tension of the film of water falls off before the thickness is reduced to 1/200,000,000 cm., and hence there probably are but few molecules in that thickness.

3. By the phenomenon of dispersion in the wave theory of light. Cauchy showed that dispersion of colors implied a granular structure in refracting media, and that the grains could not be indefinitely small, but must exceed 1/10,000 of the shortest wave length; and to produce the observed effect Lord Kelvin concluded that the number of molecules in a wave length would have to be from 200 to 600. Nobert ruled lines on glass at the rate of 40,000 to the centimeter,[2] or about two to the wave length of blue light (about 4/100,000 centimeter); and as this left the ruled surface capable of reflection, the number of molecules in the ridges between the grooves must have been sufficient to give solid body to the sculptured mass, and thus not less than several hundred to the wave length. If the mean free path in a solid like glass be 25 times the diameter of the atom itself, this will make the diameter of the atoms of the order of 1/400,000,000 of a centimeter.

4. By calculating the length of the average free path of a molecule in a gas, according to the kinetic theory. Loschmidt in 1865, Stoney in 1866, and Lord Kelvin in 1870, independently reached similar results, namely, for the average free path about 1/100,000 of a centimeter, and for the diameter of the gaseous molecule about 1/500,000,000 of a centimeter.

These four methods of estimating the diameter of atoms thus agree very closely among themselves; and moreover a similar result on the average distance of molecules deduced by entirely different

[2] Referring to Nobert's lines Maxwell says: "A cube, whose side is the 400th of a millimetre, may be taken as the *minimum visible* for (microscopic) observers of the present day. Such a cube would contain from 60 to 100 million molecules of oxygen or nitrogen" (cf. The article "Atom," Encyclopedia Britannica, ninth edition, p. 42). If there be 400 molecules in a line the length of the edge of the cube just considered, the cube would contain 64,000,000, which agrees with Maxwell's estimate. A line equal to the wave length of blue light would thus contain 250 molecules.

considerations was obtained by M. Lippmann, in a paper read to the Paris Academy of Sciences, October 16, 1882.

In his "Popular Lectures and Addresses" (vol. 1, p. 224) Lord Kelvin condenses his conclusions as follows:

"The four lines of argument which I have now indicated lead all to substantially the same estimate of the dimensions of molecular structure. Jointly they established, with what we cannot but regard as a very high degree of probability, the conclusion that, in any ordinary liquid, transparent solid, or seemingly opaque solid, the mean distance between the centres of contiguous molecules is less than the 1/5,000,000 and greater than the 1/1,000,000,000 of a centimeter.

"To form some conception of the degree of coarse-grainedness indicated by this conclusion, imagine a globe of water or glass, as large as a football,[1] to be magnified up to the size of the earth, each constituent molecule being magnified in the same proportion. The magnified structure would be more coarse grained than a heap of small shot, but probably less coarse-grained than a heap of footballs."

§ 11. *On the Molecular Constitution of Matter and on the Penetrability of Solids by Fluids.*—In his address on "Mathematical Physics" at the St. Louis Congress of Arts and Sciences in 1904, Poincaré speaks of the porosity of matter as follows:

"The astronomical universe consists of masses, undoubtedly of great magnitude, but separated by such immense distances that they appear to us as material points; these points attract each other in the inverse ratio of the squares of their distances, and this attraction is the only force which affects their motion. But if our senses were keen enough to show us all the details of the bodies which the physicist studies, the spectacle thus disclosed would hardly differ from the one which the astronomer contemplates. There too we should see material points separated by intervals which are enormous in comparison with their dimensions, and describing orbits according to regular laws. Like the stars proper, they attract each other or repel, and this attraction or repulsion, which is along the line joining them, depends only on distance." (Cf. *Bulletin of the American Mathematical Society,* February, 1906, p. 241; authorized translation by Professor J. W. Young.)

Professor Sir G. H. Darwin's recent presidential address to the British Association for the Advancement of Science at Cape Town, 1905, was devoted largely to the discovery of electrons. After treating of these subatomic corpuscles he adds:

"I have not as yet made any attempt to represent the excessive minuteness of the corpuscles, of whose existence we are now so confident; but, as an introduction to what I have to speak of next, it is necessary to do so.

[1] Or say a globe of 16 centimeters diameter.

To obtain any adequate conception of their size we must betake ourselves to a scheme of threefold magnification. Lord Kelvin has shown that if a drop of water were magnified to the size of the earth the molecules of water would be of a size intermediate between that of a cricket ball and of a marble. Now each molecule contains three atoms, two being of hydrogen and one of oxygen. The molecular system probably presents some sort of analogy with that of a triple star; the three atoms replacing the stars, revolving about one another in some sort of a dance which cannot be exactly described. I doubt whether it is possible to say how large a part of the space occupied by the whole molecule is occupied by the atoms; but perhaps the atoms bear to the molecule some such relationship as the molecule to the drop of water referred to. Finally, the corpuscles may stand to the atom in a similar scale of magnitude. Accordingly, a threefold magnification would be needed to bring these ultimate parts of the atom within range of our ordinary scales of measurement. . . .

"The community of atoms in water has been compared with a triple star, but there are others known to the chemists in which the atoms are to be counted by fifties and hundreds, so that they resemble constellations."

Such general discussions by these illustrious physicists, Kelvin,[1] Poincaré and Darwin, are not to be construed too literally, and yet they clearly indicate the general belief among the foremost men of science that the spaces between the particles of matter are immense in comparison with the dimensions of the particles themselves.

From Lord Kelvin's discussion of the size of atoms treated in the above section, we have seen that the diameters of these bodies is of the order of 1/500,000,000 of a centimeter, or 1/1,270,000,000 of an inch. The average space between the molecules being 1/100,000 of a centimeter, or about 5,000 times the diameter, is of the order of 1/254,000 of an inch. This is decidedly below the

[1] In a well-known paper on gravitating matter, Lord Kelvin compares the stars of the Milky Way to the atoms of a bubble of gas. For a giant for whom our suns would be what atoms are to us, the stars would be beyond the reach of the keenest vision and the Milky Way appear to behave as a gaseous medium. M. Poincaré has discussed the problems of the universe from this point of view in an address to the Astronomical Society of France (*Bulletin Astronomique de la Societé Astronomique de France,* April, 1906; an excellent translation in *Popular Astronomy* for October, 1906). It is remarkable that Democritus, founder of the atomic theory among the Greeks (460–360 B. C.), should also have recognized that the Milky Way is composed of a mass of stars too dense to be seen separately by the unaided vision (cf. "Aristotle's Meteorology," Lib. I., Ch. VIII., Sec. 4). Thus Lord Kelvin's conceptions do not differ greatly from those of Democritus of Abdera, though the modern theories are much better established than the atomic theories were among the Greeks.

limit of resolution of the microscope which has been estimated by Michelson at 1/100,000 of an inch.

Now in our discussion of the constitution of granites we found that the *visible pores* in the quartz matrix have all diameters down to less than 1/10,000 of an inch, and thus practically to the lowest limit visible in the microscope. These visible pores thus evidently connect directly with the smaller invisible spaces which separate the molecules. As the diameters of the molecules in water vapor are only about 1/5,000 of the spaces between them, the triple atom of hydrogen and oxygen constituting water or water vapor would have ample facilities for penetrating a spongy and cavernous mass like granite with innumerable holes frequently of large size but always at least equal to the average free path. If the water or vapor were under pressure, so as to condense the fluid and thus increase the number of vibrations of a molecule per second, the rate of penetration of the fluid obviously would be much augmented.

And since granite not only is filled with pores of these various sizes, but also everywhere more or less cleft by planes of crystalline structures which are not really tight, but full of fissures and thus inviting the penetration of the fluid by the full power of capillary forces, we see that water would necessarily penetrate it at a fairly rapid rate. At the same time the influence of capillarity in such a structure is so great that although water might enter and slowly pass through it, even the development of steam pressure beneath the layer would not force the fluid back, because the steam pressure is nullified an infinitely small distance from where it is exerted, on account of capillary resistance; yet the fluid may keep on descending under the suction of the capillary forces so long as the supply from above is not cut off.

Upon these physical grounds it seems clear that there must be a secular leakage of the ocean bottoms, and a corresponding development of steam beneath the earth's crust. The steam expands the rock in which it is absorbed and in seeking release thus brings on earthquakes and mountain formation.

Even if the pressure due to depth should tighten up the structure of the rock in the lower layers of the crust, it would not be able to obliterate the leakage depending on the pores and crystalline structure. It is evident that at depths such as twenty miles the downward movement of the fluid would continue, though very slowly. Hence the leakage of the oceans is extremely gradual, and the recurrence of earthquakes visibly delayed after relief has once been obtained. Thus while the tightness of the earth's crust due to the grain of the rock and the pressure to which it is subjected in the lower parts does not prevent ocean leakage, it makes the process so slow and gradual as to afford considerable protection to life upon our planet.

II. On the Physical State of the Earth's Interior, on the Average Rigidity of the Globe as a Whole, and on the Substratum of Plastic Matter Beneath the Crust which in Earthquakes Behaves as Fluid.

§ 12. *On the Theory of a Fluid Globe Held by the Older Geologists, and on Hopkins' Argument for Solidity Based on the Phenomena of Precession and Nutation.*—In the early part of the nineteenth century it was generally believed by geologists that the earth was a liquid globe covered by a rocky crust much thinner in proportion to the diameter than the shell is to that of an egg. This supposed liquid interior had been suggested by the streams of molten lava often observed to issue from volcanoes, and by the igneous rocks so abundantly poured forth in many places. The theory of a fluid globe seemed to be confirmed by the observed increase of temperature downward, which would give rise to molten rock at a depth of some twenty miles. The mountains and other phenomena traceable to dislocations of the crust could all be explained by a solid layer of this thickness, and the natural inference was that the great central nucleus remained liquid. The consolidation of the globe was ascribed to the progress of secular cooling, from the primitive state of high temperature assumed by Laplace in the nebular hypothesis postulated for explaining the origin of the solar system.

The older geologists had not adequately considered the effects of pressure in augmenting the solidity of the globe as we go downward; for since pressure raises the melting point of solids, the matter of the nucleus, though highly heated, might be solid if the pressure be great enough to prevent fusion under the prevailing temperature. In order to throw light upon this question, Hopkins of Cambridge, England, took up the problem in 1839 (*Phil. Trans.*, 1839; "Researches in Physical Geology," 1839–1842), and sought to prove from the observed phenomena of precession and nutation that the earth could not be composed of a thin shell some twenty miles thick, filled with liquid. He concluded that the crust could not be less than 800 to 1,000 miles thick, and that the globe might even be solid to the center, except some small vesicular spaces here and there filled with molten rock.

In 1868 this subject was examined by the eminent French astronomer, Delaunay, who published a paper on "The Hypothesis of the Interior Fluidity of the Globe" (C. R. Acad. des Sci., Paris, July 13, 1868), in which he threw doubt on the views of Hopkins, and suggested that if the earth's nucleus were a mass of sufficient viscosity it might behave as if it were solid, and hence concluded that the observed phenomenon of precession and nutation did not necessarily exclude a fluid nucleus.

§ 13. *Lord Kelvin's Earliest Studies on the Precession of a Spheroid Containing Liquid.*—Lord Kelvin had already taken up the problem of the internal state of the earth in 1862, and considered the effects of a fluid nucleus enclosed in a thin shell when the whole mass was subjected to tidal strains. As the shell must yield under these strains the land would be carried up and down with the superjacent sea, and if such yielding occurred it ought to be sensible to observation. But since the sensible obliteration of the tides had not been observed, he naturally inclined to the view of Hopkins that the earth is effectively rigid and behaves as a solid globe.

In reply to Delaunay's criticism Lord Kelvin pointed out that if the French astronomer had worked out the problem mathematically he could not fail to see that the hypothesis of a viscous and quasi-rigid interior "breaks down when tested by a simple calculation of the amount of tangential force required to give to any globular portion of the interior mass the precessional and nutational motions which, with other physical astronomers, he attributes to the earth as a whole." (*Nature*, February 1, 1872.) On making this calculation Lord Kelvin found that the earth's crust down to depths of hundreds of kilometers must be capable of resisting a tangential stress of nearly 0.1 of a gramme weight per square centimeter; this would rapidly draw out of shape any plastic substance which could be properly called a viscous fluid. "An angular distortion of 8″ is produced in a cube of glass by a distorting stress of about ten grammes weight per square centimeter. We may therefore safely conclude that the rigidity of the earth's interior or substance could not be less than a millionth of the rigidity of glass without very sensibly augmenting the lunar nineteen yearly nutation." (*Nature*, February 1, 1872, p. 258.)

Notwithstanding these early criticisms of Delaunay's paper, Lord Kelvin subsequently concluded that the phenomena of precession and nutation do not decisively settle the question of the earth's internal fluidity. Yet the semiannual and lunar fortnightly nutations may be considered to disprove absolutely the existence of a thin rigid shell full of liquid. If the fluid were arranged in successive layers of equal density, the only nutational or precessional influence exerted upon it would depend on the non-sphericity of the shells. "A very slight deviation of the inner surface of the shell from perfect sphericity would suffice," according to Lord Kelvin, "in virtue of the quasi-rigidity due to vortex motion, to hold back the shell from taking sensibly more precession than it would give to the liquid, and to cause the liquid (homogeneous or heterogeneous) and the shell to have sensibly the same precessional motion as if the whole constituted one rigid body." (Sir W. Thomson, British Assoc. Report, 1876, Sections, p. 5.)

It will be seen from this discussion that the argument from precession and nutation is only in part conclusive. If the fluid had a viscosity approaching high rigidity for rapidly acting forces, or it were subjected to such pressure that the particles in confinement acquired the properties of a solid, there would evidently be no sensible deviation from the precession and nutation appropriate to a cold solid globe.

§ 14. *On Lord Kelvin's Researches on the Earth's Rigidity Based on the Analysis of the Tides.*—The state of the earth's interior had early engaged the attention of Lord Kelvin, for the propagation of heat through the crust was before him as early as

1846. ("De Motu Caloris per Terræ Corpus," read before the faculty of the University of Glasgow in 1846; also a "Note on Certain Points in the Theory of Heat," February, 1844, published in the *Cambridge Mathematical Journal,* and reprinted in the "Mathematical and Physical Papers of Sir W. Thomson," 1882, Vol. I, Art. X.)

In a paper "On the Rigidity of the Earth" published in the *Philosophical Transactions of the Royal Society* for May, 1862, Lord Kelvin pointed out that if the matter of the earth's interior yielded readily to the tidal forces arising from the attraction of the sun and moon, the crust itself would respond to these forces in much the same way as the waters of the sea; and the corresponding movements of the crust would mask or largely reduce the height of the oceanic tides calculated for a rigid earth. By actual analysis of long series of tidal observations Kelvin and Darwin subsequently found the observed fortnightly tide to have very nearly its full theoretical height, and hence concluded that our globe as a whole possesses a very high effective rigidity. (Cf. Thomson and Tait's "Natural Philosophy," Vol. I, part II, § 832–847; also the article "Tides," Encyclopedia Britannica, ninth edition, § 44.)

Owing to the great importance of this work on the rigidity of the earth, we must trace the successive steps in the advancement of our knowledge. The assumption that the earth is made up of a liquid nucleus covered with a thin crust stiff enough to maintain its figure against the tide-raising forces of the sun and moon would imply that the crust has a degree of strength and rigidity not possessed by any known substance. It was therefore inferred by Lord Kelvin as early as 1862 that the crust might be 2,000 to 2,500 miles thick, in order to resist distortion under the tide-producing forces arising from the sun and moon.

"If the crust yielded *perfectly,* there would be no tides of the sea, no rising and falling relatively to the land, at all. The water would go up and down with the land, and there would be no relative movement; and in proportion as the crust is less or more rigid the tides would be more or less diminished in magnitude. Now we cannot consider the earth to be absolutely rigid and unyielding. No material that we know of is so. But I find from calculation that were the earth as a whole not more rigid than a similar globe of steel the relative rise and fall of the water in the tides would be only two-thirds of that which it would be were the rigidity perfect; while, if the rigidity were no greater than that of a globe of glass, the relative rise and fall would be only two-fifth of that on a perfectly rigid globe.

"Imperfect as the comparison between theory and observation as to the actual height of the tides has been hitherto, it is scarcely possible to believe that the height is only two fifths of what it would be if, as has been universally assumed in tidal theories, the earth was perfectly rigid. It seems, therefore, nearly certain, with no other evidence than this afforded by the tides, that the tidal effective rigidity of the earth must be greater than that of glass. This is the result taking the earth as a globe uniformly rigid throughout. That a crust fifty or a hundred miles thick could possess such preternatural rigidity, as to give to the mass, part solid and part liquid, a rigidity as a whole, equal to that of glass or steel is incredible; and we are forced to the conclusion that the earth is not a mere thin shell filled with fluid, but is on the whole or in great part solid." (Paper read to Geological Society of Glasgow, February 14, 1878; Kelvin's "Popular Lectures and Addresses," Vol. II, pp. 317–318.)

In his presidential address to the Mathematical and Physical section of the British Association at Glasgow, September 7, 1876, Lord Kelvin remarked of the earth's crust that "were it of continuous steel and 500 kilometers thick, it would yield very nearly as much as if it were india rubber to the deforming influences of centrifugal force and of the sun's and moon's attractions." "The solid crust would yield so freely to the deforming influence of sun and moon that it would simply carry the waters of the ocean up and down with it, and there would be no sensible rise and fall of water relatively to the land." ("Popular Lectures," Vol. II., pp. 251–2.)

Lord Kelvin's final conclusion was that "the earth as a whole is certainly more rigid than glass, but perhaps not quite so rigid as steel."

§ 15. *Darwin's Researches on the Tidal Method of Evaluating the Earth's Rigidity.*—As the natural successor of Lord Kelvin in the researches on the physics of the earth, Professor Sir G. H. Darwin took up the problem of the earth's internal physical condition and confirmed and extended these conclusions by several important lines of inquiry. Darwin's researches on the bodily tides of viscous and semi-elastic spheroids and on the oceanic tides upon a yielding nucleus tended to strengthen the argument for a high effective rigidity so decidedly that he concluded that "no very considerable portion of the interior of the earth can even distantly approach the fluid condition."

But whilst Darwin's researches confirmed Kelvin's conclusions as to the great effective rigidity of the earth, yet a more critical examination of the method for calculating the fortnightly tide led to the conviction that Laplace's argument is regard to the effects of friction was unsatisfactory. That friction would greatly effect the motion of the water in slow ocean currents within a few days was seen to be untenable. In consequence of this defect it turned out that long period tides as short as a fortnight would not enable the physicist to evaluate the rigidity of the earth, though the 18.6 yearly tide, depending on the revolution of the Moon's nodes, if it can be determined by observation, will eventually give the desired result. The height of this 18.6 yearly tide, however, is only one third of an inch at the equator, and great accuracy will be required for its detection.

Acting on the old belief Darwin compared the lunar fortnightly and monthly tides observed for 33 years at various Indian and European ports, with the equilibrium theory, and found that the tide-heights were about two thirds of the theoretical height. Accordingly he remarks: "On the whole we may fairly conclude that, whilst there is some evidence of a tidal yielding of the earth's mass, that yielding is certainly small, and the effective rigidity is at least as great as that of steel." (Thomson and Tait's "Nat. Phil.," Vol. 1, Part II, § 848.)

This was written prior to the discovery of the theoretical defect in the method of calculating the height of tides with periods not exceeding a fortnight in duration; yet even after the discovery of this defect it was still possible to infer that tides of long period in oceans such as ours must conform much more nearly to the equilibrium laws than do the tides of short period. "Whilst, then, this precise comparison with the rigidity of steel falls to the ground, the investigation remains as an important confirmation of Thomson's conclusion as to the great effective rigidity of the earth. . . . It appears by numerical calculation on viscous and elastico-viscous tides that in order that the oceanic semi-diurnal tide may have a value equal to two thirds of the full amount on a rigid globe, the stiffness of the globe must be about twenty thousand times as great as that of pitch at freezing temperature, when it is hard and brittle." (Sir G. H. Darwin, article "Tides," Ency. Brit., §§ 44–45.)

§ 16. *On the Rigidity of the Earth as found by Comparing the*

Observed Period of the Polar Motion Arising in the Variation of Latitude with the Theoretical Eulerian Period Calculated for a Rigid Earth.—The detection of the variation of latitude by Küstner at Berlin in 1890–91 and the subsequent discussion by Chandler of long series of observations showing that the movement of the pole in the body of the earth has a period of some 427 days, instead of the 305 days long ago inferred from Euler's theory of the rotation of a rigid spheroid, led Professor Newcomb to point out that this observed prolongation of the theoretical Eulerian period indicates some yielding of the matter of the globe under the stresses to which it is subjected by the movement of the pole, and would afford a new method of evaluating the earth's rigidity. In his well-known paper on the "Dynamics of the Earth's Rotation" (*Monthly Notices, R. A. S.*, March, 1892) Newcomb showed that the results already obtained decidedly confirmed Darwin's conclusion that the rigidity of the globe as a whole is comparable to that of steel.

The essential point in Newcomb's explanation is that when the pole changes its position in the body of the globe, the distribution of centrifugal force shifts with respect to the solid earth, which is thus put into a state of stress and must yield to the forces acting upon it, like any other elastic solid body; the periodic deformation of the earth's figure operating to lengthen the period of the free nutation, by an amount depending on the average rigidity of the whole earth.

The continued investigation of the variation of latitude carried out at the various international latitude observatories by Albrecht and others confirms this observational result, and the subject has also been examined theoretically by Darwin, Hough, Larmor and others; so that the validity of the method suggested by Newcomb is generally recognized.

In 1896 Mr. S. S. Hough treated of the problem in a very thorough manner in his well-known paper, "On the Rotation of an Elastic Spheroid" (Phil. Trans., A, 1896). He considered chiefly the case of an incompressible homogeneous spheroid, and was enabled to show by rigorous methods that the rigidity of the earth in all probability slightly exceeds that of steel.

In a remarkable paper "On the Period of the Earth's Free

Eulerian Precession," read to the Cambridge Philosophical Society, May 25, 1896, Professor Larmor showed how to estimate the effect of the elastic yielding of a rotating solid on the period and character of the free precession of its axis of rotation, and again confirmed the high effective rigidity of the earth from another point of view.

The observed prolongation of the Eulerian period is thus fully explained by the imperfect rigidity of the earth's mass, and the high rigidity thus deduced has naturally strengthened the earlier conclusions of Kelvin and Darwin drawn from the study of the long period tides of the sea.

This investigation, like those already cited, gives us only an average effect for the earth as a whole, but does not tell us the law of the distribution of rigidity within the globe. If this law of distribution of rigidity could be found, even approximately, it would be of great interest, because we could then see in what part of the globe the principal part of the yielding takes place; and this would give us a much better understanding of the internal constitution of our planet than heretofore has been considered possible.

§ 17. *Rigidity of the Earth Calculated from the Theory of Gravity, on the Hypothesis that the Distribution of Rigidity in the Globe is Everywhere Proportional to the Pressure.*—It has not been supposed by previous investigators that a method could be devised for deducing the rigidity of a body like the earth from the theory of gravity; but in 1905 it occurred to the present writer that such a method could be found if we could adopt a suitable hypothesis for the variation of the rigidity with the pressure. Previous investigations of the internal state of the heavenly bodies had justified the law of Laplace as giving an excellent approximation to the law of density for the earth and the rest of the encrusted planets; and the monatomic law had been found most satisfactory for the sun and fixed stars (cf. *A. N.*, 4053). These laws enable one to obtain the pressure at every point of the radius of the heavenly bodies. For in several ways Laplace's law of density is fairly well established for the earth, and on equally good grounds the density of the sun is believed to conform essentially to the monatomic law.

From a study of the laws of density, pressure and temperature within the heavenly bodies it appeared to me (as it had independently appeared to Arrhenius five years before) that matter under these extreme conditions must be essentially gaseous; and as it is above the critical temperature, it is made to behave in confinement as an elastic solid. Now in all gaseous masses the density is proportional to the pressure so long as the gas remains perfect; and the gas does not cease to be perfect when the temperature is above the critical value, though it may acquire in confinement the property of an elastic solid if the pressure be great enough to bring the molecules within a distance at which the molecular forces become effective in spite of the high temperature. Thus while the property of rigidity in cold solids depends wholly on molecular forces which prevent deformation, this property for gaseous matter in confinement under such pressure that it acquires the property of an elastic solid, is due wholly to the pressure. The molecular forces giving effective rigidity must increase in proportion to the pressure, or in a higher ratio.

If according to hypothesis the matter is made solid by pressure, then the molecular forces resisting deformation in the imprisoned matter thus solidified cannot resist deformation in a less degree than the direct proportion to the pressure on which the solidification depends. And any ratio higher than the direct proportionality to the pressure would most likely depend on the temperature. Now the temperature in the earth is supposed to be everywhere such as to make the density conform essentially to Laplace's law; and the pressure resulting from this law of density gives the matter everywhere the property of an elastic solid, and therefore its molecular properties must correspond to the physical state determined by the laws of density and pressure.

It is of course conceivable that some parts of the globe might be relatively more rigid than is required to give solidity, but the effect of this would only increase the average rigidity of the earth as a whole. And since seismological and other observations seem to show that the globe is solid throughout, except a thin layer just beneath the crust, the hypothesis of a rigidity proportional to the pressure will give a true minimum value of the earth's rigidity.

Now on the hypothesis that the density follows Laplace's law, the pressure throughout the earth's mass is given by the formula (cf. *A. N.*, 4104)

$$p = \frac{3x}{2(\sigma_1 g)q^2}[(\sigma g)^2 - (\delta g)^2], \tag{1}$$

where r is the radius of the earth, g mean gravity, q the constant for Laplace's law, 2.52896 radians $= 144° \ 53' \ 55''.2$, σ the density at any point, δ the density at the surface, and σ_1 the mean density.

To render this expression available for integration throughout the sphere occupied by the earth's mass, we must put for σ^2 its value

$$\sigma^2 = \sigma_0^{\ 2}\frac{\sin^2(qx)}{q^2x^2},$$

and for δ^2 its value

$$\delta^2 = \sigma_0^{\ 2}\frac{\sin^2 q}{q^2},$$

corresponding to the surface where $x = 1$. Thus we obtain

$$p = \frac{3(\sigma_0 g)^2 r}{2(\sigma_1 g)q^2}\left[\frac{\sin^2(qx)}{q^2x^2} - \frac{\sin^2 q}{q^2}\right]. \tag{2}$$

For the total pressure throughout a sphere of radius $\rho = rx$, r being the external radius, and $x = (\rho/r) =$ fraction of the radius, we have

$$\begin{aligned} P &= \int_0^x p \cdot 4\pi r^2x^2 \cdot r dx \\ &= \frac{3(\sigma_0 g)^2 \cdot r4\pi r^3}{2(\sigma_1 g)q^4}\left(\int_0^x \frac{\sin^2(qx)}{x^2}x^2dx - \sin^2 q\int_0^x x^2dx\right), \end{aligned} \tag{3}$$

which by integration becomes

$$P = \frac{3(\sigma_0 g)^2 r4\pi r^3}{2(\sigma_1 g)q^4}\left(\frac{qx - \sin(qx)\cos(qx)}{2q} - \sin^2 q\frac{x^3}{3}\right). \tag{4}$$

As our integration is to include the whole sphere of the earth, we put $x = 1$, and then we have

$$P = \frac{3(\sigma_0 g)^2 \cdot r4\pi r^3}{2(\sigma_1 g)q^4}\left(\frac{q - \sin q\cos q}{2q} - \frac{\sin^2 q}{3}\right). \tag{5}$$

The total volume of the earth is $(4/3)\pi r^3$, and hence the average pressure per unit of area on all concentric spherical surfaces is

$$R=\frac{P}{\frac{4}{3}\pi r^3}=\frac{3}{4\pi r^3}\int_0^x p\cdot 4\pi r^2x^2\cdot rdx \qquad (6)$$
$$=\frac{9(\sigma_0 g)^2\cdot r}{2(\sigma_1 g)q^4}\left(\frac{q-\sin q\cos q}{2q}-\frac{\sin^2 q}{3}\right).$$

If r is expressed in meters, the mean pressure or mean rigidity R comes out in kilograms per square meter. To reduce the result to atmospheres we divide by 10,333. The result for the earth is $R=748{,}843$ atmospheres, about the rigidity of wrought iron.

This method takes no account of the earth's solid crust, and is therefore too small; moreover viscosity increases within the earth, owing to the rise of temperature downward. We give hereafter an approximation to the increase of rigidity by determining the mean rigidity of the earth's *matter,* as distinguished from that of the *various layers* composing the globe, just found by the above analysis.

To find the mean rigidity of the earth's *matter* we must consider not only the pressure but also the density or mass per unit volume of the imprisoned matter in each layer. The result represents a mean rigidity in which every elementary spherical shell composing the globe is allowed a weight proportional to its mass, which is multiplied by the pressure to which it is subjected.

The theory of the determination of the mean rigidity of the earth's matter is as follows:

$$P'=\int_0^x p\cdot 4\pi r^2x^2\cdot rdx\cdot\sigma=4\pi r^3\sigma_0\int_0^x p\cdot x^2dx\frac{\sin(qx)}{qx}. \qquad (7)$$

Substituting for p its value from (2), we get

$$P'=\frac{3(\sigma_0 g)^2\cdot r\cdot 4\pi r^3\sigma_0}{2(\sigma_1 g)q^5}\left(\int_0^x\frac{\sin^3(qx)x^2dx}{x^3}-\sin^2 q\int_0^x\frac{x^2\sin(qx)dx}{x}\right), \quad (8)$$

$$=\frac{3(\sigma_0 g)^2\cdot r\cdot 4\pi r^3\cdot\sigma_0}{2(\sigma_1 g)q^5}\left(\int_0^x\frac{\sin^3(qx)qdx}{qx}-\sin^2 q\int_0^x\frac{x\sin(qx)qdx}{q}\right). \quad (9)$$

The integral of this last term is $-\sin^2 q\ \dfrac{\sin(qx)-qx\cos(qx)}{q^2}$.

The value of the first integral is most conveniently found by quadrature, table for which is given in *A. N.*, 4104, p. 379. Dividing out the mass, or volume of the sphere by the density, we have

$$R' = \frac{P'}{\frac{4}{3}\pi\sigma_1 r^3} = \frac{3\int_0^x p \cdot 4\pi r^2 x^2 \cdot r dx \cdot \sigma}{4\pi\sigma_1 r^3} \tag{10}$$

$$= \frac{9(\sigma_0 g)^2 \cdot r \cdot \sigma_0}{2(\sigma_1 g) q^6 \sigma_1}\left(\int_0^x \frac{\sin^3(qx) q dx}{qx} - \frac{\sin^2 q}{q^2}\left[\sin(qx) - qx\cos(qx)\right]\right).$$

On putting $qx = 144° \; 53' \; 55''.2$, the value of the integral is found by quadrature to be 0.9592502, and when the rest of the formula is reduced to numbers we have (*A. N.*, 4104):

$$R' = 1028702 \text{ atmospheres.}$$

The rigidity of nickel steel is taken to be 1,000,000 atmospheres. It thus appears from this calculation that the average rigidity of all the earth's matter somewhat exceeds that of nickel steel. The actual rigidity of the earth almost certainly lies between the limits thus established, namely $R = 748{,}843$, based on the rigidity of the layers deduced from the pressure to which they are subjected, and $R' = 1{,}028, 702$, derived from the product of the mass of each layer by the pressure acting upon it.

In the paper, "Researches on the Rigidity of the Heavenly Bodies," *A. N.*, 4104, the rigidity of the earth is discussed as follows:

"When one considers the effects of the enclosing crust and the viscosity of the whole earth, which must be assumed to increase towards the centre, owing to the increasing density and rising temperature of the imprisoned matter, it seems not improbable that the actual effective rigidity of our globe may be nearer the upper limit than the lower, and probably we shall not be far wrong in concluding that it is approximately equal to that of nickel steel.

"Leaving aside the consideration of the effects of the solidified crust, it is evident from the nature of the forces at work that most of the yielding of our globe, due to the periodic action of small forces, is in the outer layers; and in general the yielding in any concentric layer may be taken to be inversely as the pressure to which the imprisoned matter is subjected. *It is remarkable that the curve of pressure as we descend in the earth becomes therefore also the curve of effective rigidity for the matter of which the earth is composed.* Thus the rigidity of the matter at the earth's center probably is at least three times that of nickel steel used in armor plate; as we approach the surface the effective rigidity constantly exceeds that of nickel steel until we come within less than 0.4 of the radius from the surface, where the pressure is less than 1,000,000 atmospheres.

"To imagine a mechanical substitute for the earth's constitution, without the introduction of pressure, suppose an alloy of adamant to give the material at the centre of such a globe, of the same size but devoid of gravitation, a hardness three times that of armor plate. The outer layers as we approach the surface must then be supposed softer and softer, until it is like armor plate at a little over 0.6 from the center, and finally a very stiff fluid near the surface. In addition to this arrangement of its effective internal rigidity the actual earth is enclosed in a spheroidal shell of solid rock analogous to granite. One can easily see that tidal forces applied to all the particles of such an artificial armored sphere would produce but very slight deformation, because of the enormous effective rigidity of the nucleus.

"The principal uncertainty in this result arises from the admissible variations in the assumed Laplacean distribution of density within the earth. Both Radau and Darwin (cf. *Monthly Notices,* Roy. Astron. Soc., December, 1899) have pointed out that considerable variations in the internal distribution of density are possible without invalidating the well-known argument drawn from the phenomenon of the precession of the equinoxes; yet on physical grounds it seems clear that pressure is the principal cause of the increase of density towards the earth's centre. And since this does not vary greatly for moderate changes in the law of density, the principle of continuity shows that the actual law of density within the earth cannot depart very widely from that of Laplace. The above value of the theoretical rigidity of the earth may therefore be taken as essentially accurate, and I think no doubt can remain that the rigidity of our earth as a whole considerably exceeds that of steel. The original conclusions of Kelvin and Darwin are therefore confirmed by the present dynamical considerations based upon the theory of universal gravitation."

In this connection we should remember that the experimental rigidity of steel is 808,000 and of glass 235,000 atmospheres. The calculated rigidity of all the matter within the globe, found by considering not only all the layers, but also the density in each layer, is found to be 1,028,702 atmospheres. Now the average rigidity must be greater than 750,000, because the stiffness of the crust and increase of viscosity downward is neglected in the gravitational method. In fact this method is not applicable to the outermost layers, because the pressure there is much less than the rigidity, and only becomes equal to the rigidity at a depth of something like one tenth of the radius, where the pressure is 320,295 atmospheres.

According to the experiments of Milne and Gray the rigidity of granite is about one sixth that of steel; and as steel has a rigidity of 808,000 atmospheres, that of granite is about 135,000 atmospheres, or a little more than one half that of glass. We may therefore take the outer layers of our globe to have a rigidity about half that of glass, and assume that at a depth of 0.1 of the radius it becomes nearly 2.5 times as great as it is at the surface.

Whether it becomes at a depth of twenty miles less than it is at the surface we cannot tell, but such a decrease is not impossible, perhaps not improbable; because at this depth the molten rock moves in earthquakes, and yet in confinement it must have a very sensible rigidity, though probably not more than half that of granite.

Accordingly, it looks as if the rigidity at the surface is about half that of glass, at a depth of 20 miles about one half that at the surface, and at the depth of 40 miles nearly the same, but increasing below that depth and at 160 miles again equal to that at the surface, and at a depth of 400 miles considerably larger yet, or about 1.4 times that of glass. Increasing below this depth according to the pressure, it becomes at the center over 3 times that of nickel steel used in armor plate. The rigidity of steel is attained at a little over 0.3 of the depth to the center of the earth. If this be the distribution of rigidity in the earth, the curve of rigidity is as follows:

This postulated fall in the rigidity just beneath the crust is probable for several reasons:

1. The temperature increases quite rapidly as we go downward, while the pressure increases proportionately more slowly, so that a depth would be reached at which the matter would become a plastic if not a viscous fluid.

2. The eruption of volcanoes and lava flows on a vaster scale show that a molten layer underlies the crust, and occasionally is forced to the surface.

3. This underlying molten rock moves in world-shaking earthquakes, and frequently is expelled from beneath the sea under the land to form mountain ranges along the coast.

4. We may prove this expulsion of lava by the observed seismic sea waves which indicate a sinking of the sea bottom, and by the simultaneous uplift of mountains and coasts.

From these considerations it follows that the earth is most nearly liquid just beneath the crust, and has the greatest rigidity at the center. As the plastic or quasi-viscous layer beneath the crust is thin, and possessed of considerable rigidity, *it too remains quiescent* *except when set in motion by the dreadful paroxysms of an earthquake.*

In tidal and other observations the earth therefore behaves as a solid, and the rigidity of the earth inferred by Kelvin and Darwin is confirmed. Yet a layer of plastic matter or quasi-viscous fluid exists just beneath the crust, and when disturbed by earthquakes gives rise to the development of ridges in the crust called mountains, chiefly by the expulsion of lava from under the sea.

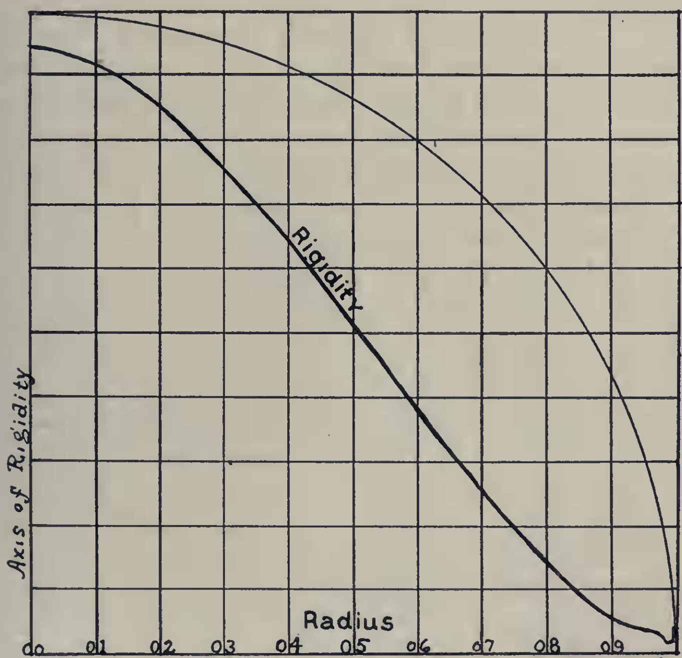

FIG. 2. Curve of Rigidity for the Earth, showing the plastic layer just beneath the crust.

§ 18. *Wiechert's Researches on the Interior Constitution of the Earth and on the Plastic or Viscous Layer which he Infers to Exist Just Beneath the Crust from Oscillations of Long Period Noticed in Seismic Vibrations.*—Professor E. Wiechert, of Göttingen, has devoted much attention to the problem of the constitution of the earth's interior. He long ago reached the conclusion that the great interior nucleus probably is a mass of iron covered with a thick shell of stony material. In the paper which he recently presented to the International Seismological Association in session at the Hague, September 21–26, 1907, he estimates the depth of the stony layer as 1,500 kilometers, which is nearly one fourth of the earth's radius.

This view that interior of the earth is metallic has been entertained by many eminent physicists, including Lord Rayleigh; but it is beset with many difficulties. We shall here mention three of the principal objections:

1. If this constitution of the earth be admitted, the curve of density will have a sudden break at a depth of about one fourth of the radius; and, as the pressure increases rapidly as we go downward, it seems improbable that the density of the outer layer could remain uniform and then change suddenly at a depth of one fourth of the distance to the center. Such discontinuity in nature seems highly improbable for the density, since there probably is no sensible discontinuity in the laws of pressure and temperature.

2. If the central nucleus is metallic, it follows that the denser elements have separated from the rest of the mass. As the matter has been essentially solid and highly rigid, owing to the pressure, ever since the globe attained anything like its present dimensions, this sinking would not be possible, because the resistance to the motion would be much too great. Thus owing to resistance to motion arising from rigidity we can not admit a separation of the denser from the lighter elements of such a globe. If the metals were all so deep down, it would be hard to account for the veins found in the crust by any kind of eruptive process, since the globe is never fissured to a depth of anything like one fourth of the radius.

3. If in addition to these mechanical objections we recall that deep down the pressure is so great as to cause an interpenetration of all the elements, whatever be the temperature, but especially under the high temperature known to prevail in the interior of the globe, so that no aggregation or crystallization of substances would be possible, and the nucleus would therefore be a magma of all the elements, it becomes inconceivable that the metals could separate from the stony elements by sinking, while the latter floated to the

surface. Even if the globe were a liquid mass of very small viscosity, it is clear that such a separation of the elements could not take place.

Finally it is to be recalled that recent experiments with radium have shown the probable transmutation of some of the metals, as when Sir Wm. Ramsay caused sulphate of copper to be partially degraded into lithium. If this can occur for one or two metallic elements, it may eventually be possible for many and perhaps all of the metals. Our knowledge of these transformations is still in its infancy, and we can not yet ascertain how minerals and metallic veins have arisen; but it is impossible to believe that the material has come up from a pure supply at a depth of 1,500 kilometers. It is much more probable that the metallic elements have been developed by differentiation and transformation from an original magma, and that the whole interior of our planet is still a magma. Differentiation of the elements appears to develop under conditions met with in the crust, but nowhere else.

Accordingly we are obliged to dissent from the constitution of the globe outlined by Professor Wiechert; but in the matter of the existence of a layer of plastic or fluid material just beneath the crust, which he infers from the long seismic vibrations with periods of about eighteen seconds, we are in hearty accord with him. This is definitely proved by the phenomena noticed in earthquakes, as more fully set forth hereafter. It is the expulsion of lava from under the margins of the sea which produces world-shaking earthquakes and the upheaval of mountains along the sea coasts.

§ 19. *On Sir G. H. Darwin's Researches on the Stresses in the Interior of the Earth Due to the Weight of Continents and Mountains.*—We have seen that the earth behaves as a solid at all depths, unless it is in the thin layer just beneath the crust, in which movements take place during earthquakes. The theory of an elastic solid shows that when such a body is stressed the state of stress is completely determined when the amount and direction of the three principal stresses are known. No limit is imposed on these stresses by theory, but in practice nature fixes a limit, beyond which the elasticity breaks down, and the solid either flows or ruptures by breaking.

In the "Nat. Phil.," Vol. I, part II, § 832, Lord Kelvin and Professor Tait remark that

"The precise circumstances under which elastic bodies break have not hitherto been adequately investigated by experiment. It seems certain that rupture cannot take place without difference of stress in different directions. One essential element therefore is the difference between the greatest and least of the three principal stresses. How much the tendency to break is influenced by the amount of the intermediate principal stress is quite unknown. The difference between the greatest and least stresses may however be taken as the most important datum for estimating the tendency to break. This difference has been called by Mr. G. H. Darwin (to whom the investigation of which we speak is due) the 'stress-difference.'"

Stress-difference is a term which when applied to matter within the earth denotes the tendency to flow. For rupture is not possible when the matter is in confinement under such pressure and at high temperature. Now if the earth were homogeneous, as assumed in Darwin's inquiry, the inequalities of surface due to the mountains, plateaus, and continents would give rise to a stress-difference in the underlying layers; and Darwin showed that the stress-difference would increase with the depth, being at the center, for inequalities of the type represented by harmonics of the second order, eight times what it is at the surface.

If the earth were not effectively solid throughout, a flow ought to take place either near the surface or at greater depth; and thus the inequalities of surface would disappear. But the plateaus and mountains do not sink in, and this fact proves that the globe is not fluid, and even that the plastic or viscous layer just beneath the crust is quite stiff. As we have seen that the rigidity increases very rapidly towards the center, we easily see why movement should not occur at great depth, since the rigidity there exceeds that of any known substance, and at the centre is about three times that nickel steel used in armor plate.

In the paper on the "Temperature of the Earth" we have shown from the evidence of stability afforded by geological pinnacles millions of years old, that no movements of deep seated character occur within the earth. This evidence supports the view that the earth is effectively solid, and has behaved as such since the consolidation of the crust.

As the rigidity increases so rapidly towards the center of the earth, flow ought not to take place at those depths; and the absence of any evidence of deep seated movements among the ruins wrought by geological time in turn supports the theory of rigidity depending on the pressure.

Darwin's hypothesis of homogeneity is only a rough approximation to the truth, and Laplace's law would no doubt give a much more exact representation of the density and the resulting stress-difference in the earth. But this suggested change of data would not greatly modify the general conclusions already stated.

§ 20. *The Theory of Isostacy.*—A more important difference might arise from the theory of isostacy, the applicability of which to the earth seems to be becoming better established by recent researches. In this view the crustal inequalities seen at the surface are compensated for by lighter or greater densities beneath, according as the crust is elevated or depressed, so that for a certain thickness of crust equal blocks have equal mass, however unequal the level of the blocks at the surface.

The recent investigations by the U. S. Coast Survey indicate that the depth of complete compensation for the United States and outlying stations is about 71 miles. No doubt a depth of something like this extent would hold true for the entire globe. If this view be admissible, it will follow that all inequalities of the crust cease to be effective at depths greater than 71 miles, and no stress-differences depending on plateaus and mountains would exist in the globe except in the layers just beneath the crust. There would thus be no stresses in the deep interior depending on the weight of continents and mountains.

This theory of isostacy is confirmed by the theory of mountain formation developed in the paper on the "Cause of Earthquakes," which shows clearly that these elevated ridges are underlaid by material lighter than the average rock of the crust. On the one hand, therefore, if stress-differences exist deep down, no movement can take place, owing to rigidity; on the other, if the theory of isostacy be admissible, no stress-differences can exist except in the outer layers of the globe, within 71 miles of the surface.

We conclude therefore that in no case could movements occur *except in the layer just beneath the crust.* These superficial movements are called earthquakes, and are caused chiefly by the leakage of the oceans. Observations show that the depth of such disturbances in all cases is less than 40 miles. This accords with the theory of isostacy, and confirms the conclusions drawn from that theory that all surface inequalities are compensated for at but a slight depth.

§ 21. *Uplifts along the Andes show that the mountains are not sinking under their own weight.*—In Professor Sir G. H. Darwin's paper on the stresses in the earth, above cited, he has also considered harmonics of high order, corresponding to the case of a series of parallel mountains and valleys, which thus corrugate a mean level surface with an infinite series of parallel ridges and furrows. Here the stress-difference depends only on the depth below the surface, and is independent of the position of the point considered with respect to ridge and furrow. Taking a series of mountains 13,000 feet (about 4,000 meters) above the valley bottoms, formed of granite of density 2.8, he shows that the maximum stress-difference is 4×10^5 grammes weight per square centimeter (about the tenacity of cast tin). And when the mountain chains are 314 kilometers apart, making the ridges about 78 times wider than they are deep, the maximum stress-difference is reached at a depth of 50 kilometers below the surface, or at a depth of 12½ times the height of the mountains above the valleys. Thus for mountains of the height of our average ocean depth, the maximum tendency to flow would be at a depth of about 31 miles. (Cf. "Nat. Phil.," Vol. I, Part II, § 832.)

If earthquake shocks were due to such flowage the mountains would be gradually reduced in height. Instead of this settling occurring, mountains like the Andes are still rising, as we may infer from the fact that after an earthquake the adjacent sea coast often is elevated and higher than before; while the sinking of the adjacent sea bottom, indicated by the accompanying seismic sea wave, shows that the bed of the sea was undermined by the expulsion of the material pushed under the land and mountains. *This state of fact emphatically contradicts the view that these great seismic disturbances are due to the flowage beneath the crust arising from the* *weight of continents and mountains.* Neither the uplift of mountains about the sea coasts, nor the earthquakes occurring in these regions can be explained by flowage beneath the crust, because the movement is positive rather than negative, as required by this theory.

Whilst the investigation of Professor Sir George Darwin therefore does not give us a clue to the observed movements, it is nevertheless very valuable as furnishing an indirect confirmation of the present theory that mountain formation depends on the sea. Observation shows that the movements are positive, and as the theory of flowage indicates that they should be negative, we may infer that whatever be the stress-differences existing beneath the earth's crust, the movements thus produced are insensible compared to those depending on the expulsion of lava from under the sea by world-shaking earthquakes.

III. The New Physical Theory of Earthquakes and Mountain Formation Based on the Secular Leakage of the Ocean Bottoms.

§ 22. *On the Plastic and Perhaps Viscous Layers Just Beneath the Earth's Crust.*—We have now examined at length the arguments in regard to the constitution of the earth's interior, and have shown that although as a whole the earth is solid, owing to the pressure to which the matter is subjected, there is a plastic layer just beneath the crust which in earthquakes is made to flow and behave almost as a viscous fluid. In this layer just beneath the crust either the pressure is not great enough to produce entire solidity, with the existing temperature, or else the solid is made to flow by the breaking down of the elasticity under the action of the earthquake forces, which are powerful enough to disturb the whole world.

Although the matter in this substratum appears to have some rigidity, it seems probable that it has not the requisite elasticity to behave as a perfect solid. We know that the layer must be nearly solid, because, if it were not so, there would be a greater tendency of the mountains to subside than actually is observed. The stress-difference in the layers just beneath the crust must be very considerable; and yet this plastic matter is so stiff that it does not flow and allow the mountains and plateaus to sink in.

Now earthquake disturbances are often complex, and consist in horizontal and vertical movements combined. We have seen that in the long run the uplifting tendency predominates, because it is in this way that the mountains and plateaus have arisen. Nevertheless there are numerous cases in which subsidences take place, and these settlements often seem to be somewhat gradual, as if the substratum was slowly yielding and flowing under the stresses to which it is subjected. These gradual subsidences, of the class that was observed by Darwin and Fitzroy at Conception in 1835, seem to afford convincing evidence that the layer beneath the crust is certainly plastic, perhaps viscous.[4] The yielding of the layer beneath the crust is shown not only in movements noticed in earthquakes, when lava is expelled from under the sea and pushed under the land; but also in the subsidences which the sea trenches experience after earthquakes. These subsidences have folded the rocks seen in mountain ranges now on land; and although most of such subsidence is due to the undermining of the troughs by the expulsion of lava, it seems likely that some very gradual yielding also takes place. The layer under the crust is therefore certainly plastic, when partially undermined, and probably so, independent of the undermining, if it is subjected to great forces, as in world-shaking earthquakes, where mountains are in process of upheaval. If the matter is also viscous, the viscosity must be very high. With the matter imprisoned beneath the earth's crust it is difficult if not impossible to distinguish between plasticity and true viscosity, because, if the fluid is very stiff, it would behave almost as a solid. And the tests heretofore afforded by earthquakes are not decisive. This view of the substratum just beneath the crust is not essentially different from the theory held by Arrhenius with regard to the interior of the earth as a whole. But this layer is the only part of the interior in which movements may be observed, and even here movements would not take place but for the steam developed beneath the crust by the secular leakage of the oceans. It may be that the future study of these movements will some day

[4] We follow Sir George Darwin in "distinguishing viscosity, in which flow is caused by infinitesimal forces, from plasticity in which permanent distortion or flow sets in when the stresses exceed a certain limit." (Letter to Sir A. Geikie, January 9, 1884.)

enable us to decide whether the substratum is plastic only, or truly viscous.

§ 23. *Substratum Everywhere Quiescent Except when Disturbed by Earthquakes.*—The fact the large areas of the earth's surface in such dry countries as Sahara, our Western Plateaus, and the interior of Australia, are quite free from earthquake disturbances, shows what would happen everywhere but for the presence of surface water, and especially the leakage of the crust depending on the sea. The quiescence of the substratum in interior regions remote from the sea shows that under normal conditions this layer is quite inert. It is only set in motion by the vapor of steam which slowly develops stresses in the rocks of the crust and finally brings on earthquakes. It might be plastic enough to yield slightly under sufficiently great forces, but the loading and unloading due to meteorological and geological causes going on in nature are not great enough to have any appreciable effect, as we may infer from the universal quiescence of inland areas, especially in desert countries.

It seems to be true, however, that when the crust is broken and upheaved, in the formation of mountains near the sea coast, some slow yielding takes place beneath. Yet at present any changes of a creeping nature can not be entirely separated from those depending on the expansion and expulsion of lava from under the sea; and we can only feel sure of the inert character of the substratum, except where disturbed by water vapor entering from without. Along the sea coasts the stresses in the crust are constantly changing, and the crust blocks yielding more or less to the stresses acting upon them; it is only when *sudden yielding* occurs that we experience a shock, and the greatest earthquakes are characterized by molten rock adjusting itself beneath the crust. It is probable that much yielding takes place which is exceedingly gradual and produces no disturbances sensible to ordinary observation. In dry regions remote from the sea there are no shocks, and therefore also no gradual yielding of the crust; hence the substratum is inherently and naturally quiescent except when disturbed by external forces.

§ 24. *Mountain Formation in the Sea and on the Land.*—In the paper on the "New Theory of Earthquakes and Mountain Formation," we have cited certain cases of mountain formation now going

Fig. 3. Relief Map of North America. (From Frye's Complete Geography, by permission of Ginn & Co., Publishers.) This map illustrates beautifully the recession of the sea since the formation of the Rocky Mountains, which were at one time the eastern border of the Pacific Ocean.

on in the depths of the sea, and directly connected with mountain systems spread out on the land. Thus we have shown that the Aleutian Islands are a branch or part of the Rocky Mountains still remaining in the depths of the sea. As this part of the chain is now being uplifted by the ocean, we get a very clear conception of how the whole Rocky Mountain system was formed. We are fortunate therefore to find a part of a great mountain chain still unfinished, with one end under water and the main body of the system high and dry along the edge of the continent.

Now no one believes[1] that mountain formation takes place far inland, because the mountains generally follow the coast, and moreover at present the process is found to be most active *in the sea,* as in the region of the Aleutian Islands and the Antandes. This geographical distribution of mountain-making is therefore a most powerful argument for the new theory. Moreover it is generally recognized that the Rocky Mountains in the United States are a good deal older than the Andes in South America; and as the relative ages bear some relation to the distances from the sea, the mountains on land give the same indication as those still in the depths of the sea. The recession of the sea goes on at very unequal rates in different parts of the world, yet the present positions of the mountains show that the older mountains are generally remote from the ocean. The present theory is therefore confirmed by the lay of the older as well as of the younger mountain systems; and by the situation of the mountains on land as well as of those now being formed in the depths of the sea. All the mountain phenomena of the globe are thus shown to be consistent. But as direct observation of mountain formation witnessed with our own eyes is the most convincing of all evidence, it is fortunate that we are able to cite numerous cases of mountain ranges now developing in the sea. By the study of the sinking going on where trenches are developing, we see how the wrinkles and valleys were produced in mountain systems now at a considerable distance from the ocean. Since the sea recedes from the mountains in the course of geological ages, it follows that more and more land is constantly rising above the water,

[1] Compare § 42 of this paper, where Leconte's views are quoted at length. He held that mountain ranges are formed on lines of thick sediment along the shores of continents.

and the continents growing larger. The mountains are formed by earthquakes, and earthquakes are due to the sea, which thus makes more and more land for the development of the higher forms of life upon the globe.

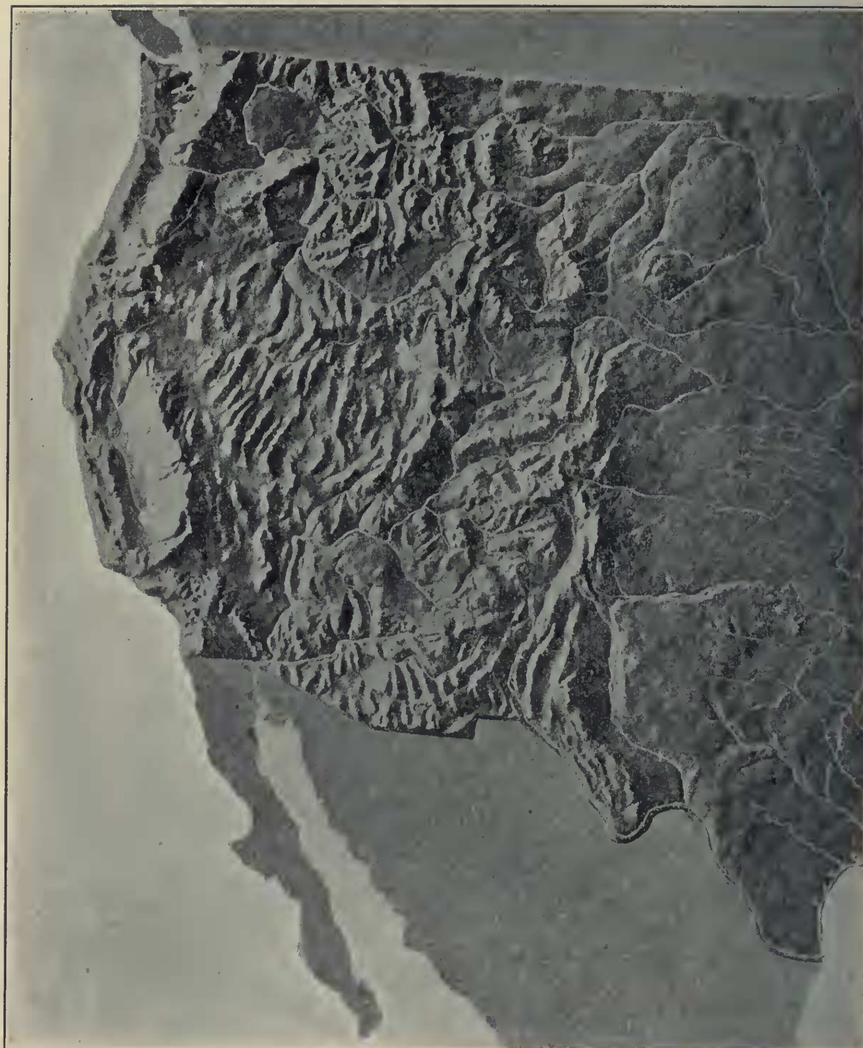

FIG. 4. Relief Map of the United States. (From Frye's Complete Geog-
especially how the great plateau west of the Rocky Mountains has been

§ 25. *The Origin of Faults in the Earth's Crust.*—It has long been recognized that faults in the earth's crust are often displaced by earthquakes. Now earthquakes are mainly submarine or follow the borders of the continents. Here the mountain ranges have de-

raphy, by permission of Ginn & Co., Publishers.) The reader should notice crumpled in the uplift from the sea, which has receded westward 1,000 miles.

veloped or are now developing, and in general the faults run along the sea coasts and into the sea, where mountain formation is in progress. Thus it is clear that faults arise from the stresses and movements of the crust produced by earthquakes and mountain formation, and therefore from the secular leakage of the ocean bottoms.

Sometimes the faults move but little, at other times they give rise to conspicuous changes of level; and where vast down-throws or uplifts have occurred certain types of mountains arise from normal faulting. The more horizontal movements of faults arise mainly in the trenches along the sea coasts, which produce the folding seen in mountain chains. The vertical movements are more general, and are especially conspicuous in elevated plateaus, like those of our western states.

In his "Report on the Geology of the High Plateaus of Utah," Washington, 1880, Major Dutton gives a description of some of the most magnificent faults in the world. On page 45 he indicates the dependence of these faults on the ancient shore line of the Eocene lake, thus:

> "It yet remains to speak of another interesting relation of the later system of faults. They have throughout preserved a remarkable and persistent parallelism to the old shore line of the Eocene lake, following the broader features of its trend in a striking manner. The cause of this relation is to me quite inexplicable, so much so, that I am utterly at a loss to think of any subsidiary facts which may be mentioned in connection with it and which can throw light upon it."

What puzzled Major Dutton most was the raising of the area of the lake; but as the whole region was uplifted by the sea in later times this phenomenon was in no way remarkable. The rocks in such disturbed regions have been broken and folded into a series of troughs and arches or thrown into domes and basins, and probably no two adjacent areas retained their relative levels throughout. His observation, however, confirms the present theory that faulting is generally parallel to the ancient sea shore, and therefore produced originally by the oceans.

The conspicuous character of the vertical movement of the crust blocks in the region of the Great Basin led several American geologists to suggest that vertical forces had operated in the uplift of these plateaus. As the whole region has been raised from the sea by the injection of the land with lava pushed under the crust from beneath the sea, it is evident that the crust blocks ought to be displaced unequally in different places, and hence the various types of faulting observed.

It should be remarked, however, that in the elevation of a plateau a mile high, only a layer of lava a mile deep needs to be injected. If three miles high, the layer would have to be three miles thick; but even this maximum height is only about one seventh of the thickness of the crust; and hence eruptions would not usually occur in these uplifts. The plateaus are all of small height compared to the thickness of the earth's crust, beneath which the movement of molten rock takes place.

If some faults should thus be widely opened, lava flows of vast extent, like those in Utah and Oregon, might be expected to occur. We cannot give the details of the cracks which produced these gigantic outflows, but it is evident that they depended on the opening of immense faults. Now the faults are produced and moved by earthquakes, and earthquakes are due to the leakage of the oceans. It follows therefore that the most immense lava flows ought to take place near the sea; and this seems to be true both in North America and in Asia, where the outflow in the plateau of Deccan has always excited the wonder of the naturalist.

That all the faults of the earth's crust depend on the sea and are produced by world-shaking earthquakes, is clearly indicated by the geographical distribution of these cracks in the crust. If any other cause, such as the secular cooling of the globe, were at work, we should find a relatively greater predominance of faults far inland, which is contrary to observation, especially in dry countries.

It is remarkable that geologists have referred so many phenomena to faulting, but have made little or no attempt to explain faulting itself. In the present theory referring the origin of faults to the expulsion of lava from under the sea we have for the first time a satisfactory and consistent view of these phenomena. Faults evidently arise mainly from the motion of lava in earthquakes, by which the overlying rocks of the crust are broken, and often displaced along the line of fracture.

When the crust is thus rent into blocks, some of them are reduced to small size, and eventually raised up, as in the vertical walls of granite now seen in Smyth's channel, southern Chile, the Straits of Magellan, Yosemite Valley, California, and the fiords of Norway. These precipitous walls of granite could be pushed up only by vertical forces, in earthquakes. It is noticeable that no such isolated masses are found towering up in the plains of Kansas, the desert of Sahara, and other inland regions far from the oceans. The origin of faults and fault movements must therefore be sought in the leakage of the oceans and in the resulting relief, which takes place in the sea bottoms and along the borders of the continents.

§ 26. *On the Uplift of the Great Plateaus of the World and on the Gradual Elevation of the Continents.*—For reasons already amply set forth in § 7, the process involved in the formation of the Andes is clear and beyond dispute. Now it happens that the Andean plateaus, such as those of Quito, Caxamarca, Cuzco and Titicaca, are generally included between the eastern and western ranges of the Andes, and were evidently uplifted by the same forces which formed the mountains themselves. Accordingly it is clear that a plateau such as that of Titicaca was therefore uplifted by the expulsion of lava from under the sea.

If now we pass from the Andes to the Himalayas, we shall find that in like manner those great mountains of Asia were uplifted principally by the Indian Ocean. The plateau of Thibet in the Himalayas of Asia corresponds exactly with that of Titicaca in the Andes of South America; and as the latter was formed with the Andes, so also the plateau of Tibet was formed with the Himalayas. This seems absolutely clear and incontrovertible. And a similar mode of development must be ascribed to the table lands to the east and west of Tibet, so that the principal plateaus of Asia, Tibet and Iran, are clearly the work of the sea.

The highest part of these plateaus is Tibet, with an average elevation of about 15,000 feet, and a width of about 500 miles at the highest part. At the middle it is somewhat wider, and to the west it narrows into Little Tibet, less than half the width of Tibet proper. It is evident that great Tibet was uplifted chiefly by movements from the direction of the bay of Bengal; this is shown by the lay of the mountain chains south of Tibet, and by the great earthquake belt still persisting in the valleys of the Ganges and Brahmaputra.

In the case of North America the plateaus are broader and correspondingly lower than those of South America and Asia. But if the sea gave rise to the uplifts connected with the Andes and Himalayas, can anyone doubt that the plateaus of North America are due to the same cause? The *total volume* of the North American

FIG. 5. Relief Map of Asia. (From Frye's Complete Geography, by permission of Ginn & Co., Publishers.) The mountains along the east coast illustrate the successive stages in the recession of the Pacific Ocean. At some future time the border of the continent will extend to the string of islands running from Kamchatka to the Philippines, the shallow seas of Japan and China becoming inland valleys.

FIG. 6. Relief Map of Africa. (From Frye's Complete Geography, by permission of Ginn & Co., Publishers.) The reader should notice how the highest mountains along the east coast face the Indian Ocean, which is a continuation of the Pacific.

plateau is comparable with that in Asia, and it is easy to see how the relief of the Pacific on our side may have taken the form of a table-land of greater width but smaller height. The numerous parallel mountain chains west of the Rocky Mountains show the nature of the mighty forces at work, and prove that this uplift was the work of the Pacific Ocean.

§ 27. *The forces which have raised the mountains and plateaus of the globe are identical with those which have raised the continents above the sea, and all these forces depend on the leakage of the oceans.*—The geological evidence of the slow operation of the forces which have uplifted the plateaus and mountains shows the immeasurable ages during which they have been at work. Sometimes large portions of a continent have risen for a time, and again slowly subsided, and thus have arisen the phenomena noted in the sedimentary rocks studied in geology. These gentle movements often are without violent earthquake shocks, because the yielding is very gradual, and the crust is slowly raised up and down without breaking. It is only where the expulsion of lava from under the sea is rapid and violent that breaking develops at such rate as to form mountain chains and plateaus. The uplift of a plateau also requires a large amount of material. Where the process is gentle and gradual a whole continent may be slowly uplifted, and this process evidently has raised the low broad plains above the water. *The cause of epeirogenic and of orogenic movements is everywhere one and the same.* The movements take different forms according to the suddenness with which the forces act; but both depend on the leakage of the oceans, and not at all on the secular cooling of the globe, the effect of which is insensible.[1]

[1] Since this was finished the writer has carefully recalculated the shrinkage of the earth's radius in 2,000 years, and finds that it can not exceed 1.5 inches. This takes no account of the increase of the interior heat of our globe due to radio-activity. If this latter effect were taken into account probably there would be no shrinkage whatever. Quite independently of these effects, however, there is an actual expansion of the globe due to the leakage of the oceans.

In the same way it is found, by the application of Fourier's theory of heat to the cooling at the surface, that the total shrinkage in the *length* of a continent such as North or South America, assumed to be equal to the terrestrial radius in length, is less than 1.5 inches. This again takes no

Such an inference seems justified by the study of the mountains and plateaus of the world, and also by the movement of the strand line which Professor Suess has so carefully traced in every country. Almost everywhere the level of the sea has been lowered in recent geological time.

During his travels in South America, Darwin recorded many observations to show that Patagonia and the whole end of the continent south of the La Plata had been recently elevated above the sea; and he mentions a channel in the Andes quite a distance north of the Straits of Magellan which gave evidence of the former passage of the sea through it. In view of these well-established facts, can any one doubt that the Straits of Magellan will eventually become dry and Tierra del Fuego be added to Patagonia? This whole region shows vast walls of rock towering vertically thousands of feet above the sea; evidently they were uplifted by earthquake forces from beneath, sometimes working quietly, and again spasmodically.

As surely as Calabria in Italy has been uplifted from the Mediterranean, by that sea, just so surely has the southern end of South America been raised up by the southern ocean. And if an end of a continent can be upraised, obviously whole continents can be uplifted. Accordingly in the leakage of the oceans and the relief taking place under the land which bounds them we have the true cause of continent-making.

Some original inequalities of surface may have existed after the detachment of the moon from the consolidating globe, but these have since been enormously increased by the effects resulting from the leakage of the oceans. As the earth gets older, the lithosphere becomes more diversified, and the face of the earth more and more wrinkled.

The situation of the great plateaus of the world facing the largest oceans gives a clear indication of the nature of the forces at work

account of radium, the effect of which would be to diminish this calculated shrinkage, or do away with it entirely. By such comparisons as these, placed along side of the large horizontal and vertical movements noticed in earthquakes near the sea, which sometimes amount to from 30 to 50 feet at a single disturbance, we see the utter untenability of the old theories heretofore current in works on geology and the related sciences. Note added July 28, 1908.

Fig. 7. Relief Map of Australia. (From Frye's Complete Geography, by permission of Ginn & Co., Publishers.) The reader should notice how the largest mountains along the east coast face the Pacific Ocean.

FIG. 8. Relief Map of Europe. (From Frye's Complete Geography, by permission of Ginn and Co., Publishers.) The reader should notice how the principal mountain chains face the Mediterranean and the Atlantic. There is a trough in the sea bottom off the Scandinavian coast to which Professor Schiaparelli has called attention.

by which these mighty uplifts have been produced. The complex folding of the mountains to the east of Tibet shows that the Pacific aided the Indian Ocean in producing this great uplift, but we cannot yet determine the relative importance of the parts played by the two oceans.

§ 28. *On the Origin of the Alps and on the Extreme Crumpling and Folding which They Exhibit.*—The remarkable crumpling and folding noticed in the Alps has long been a matter of surprise and wonder to the naturalist. This phenomenon has always presented great difficulty to those who have attempted to explain the origin of the Alps. In the paper on the "Cause of Earthquakes" (§§ 14, 16, 18, 23) we have outlined the theory of how the Alps were formed by the sea, and criticised the old theories as totally inadequate to account for the observed crumpling. We propose here to develop the new theory a little further, and to show how it accounts for all the facts observed in a range such as the Swiss Alps, which are generally recognized as about the most complex system of mountains known upon the globe. If the new theory will explain the Swiss Alps, it will obviously explain any other mountain system in the world. The test of the theory as applied to the Alps may therefore be regarded as an *experimentum crucis*.

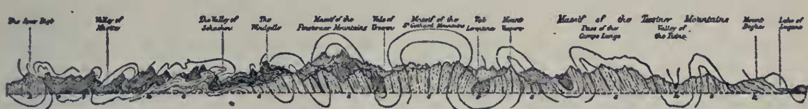

FIG. 9. Complex Folding. Section Across the Alps from the Neighborhood of Zürich toward Como; about 110 miles. (Heim and Prestwich.)

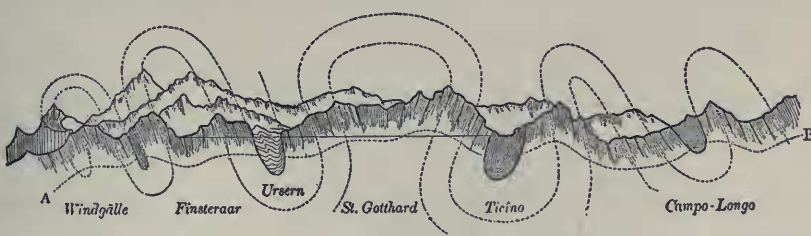

FIG. 10. Section through the Alps, Showing the Effects of Complex Folding. (From Heim's Gebirgsbildung.) The line of the St. Gotthard Tunnel and the plane of equal temperature, *AB*, beneath it, are compiled from F. Giordano, in *Bolletino del R. Comitato Geologico d'Italia,* Vol. XI., 1880, pp. 408–50.

The accompanying figures exhibit: (1) A general section of the Alps from Zürich to Lake Como (Heim and Prestwich), and (2) a section on a larger scale of a portion of the central Alps (from *Heim's Gebirgsbildung*) with fan-shaped folds and inversion of strata on the two sides. It can hardly be assumed that these illustrations are extremely accurate, but no doubt they are free from large errors in exhibiting the general character of the folding, which gives here and there fan-shaped structures with overturned dips at the sides.

Now the explanation of such structures is the most difficult problem heretofore presented to the geologist. They exhibit conspicuous lateral and vertical movements which cannot well be accounted for by the contraction theory. A shortening of about 74 miles (Heim) in the folding, which has amounted to 50 per cent. of the whole span of crust (Leconte), can not be accounted for, on the old theory, without assuming that the crust is loose from the globe, so that a vast amount of slack could be brought forward and concentrated in the folds at one point, in the Swiss Alps. This is clearly unthinkable. On the other hand, the cone of matter underlying the Alps with vertex at the center of the earth could not be sufficiently condensed to give the required slack in the overlying crust without increasing the density of the cone by 50 per cent., which could easily be detected by geodetic observations, owing to the resulting deviations of the plumb line. Accordingly we may feel sure that the matter under the Alps not only is not denser than the average, but actually lighter, by an appreciable amount. The crumpling of the Alps cannot therefore be due to condensation beneath these mountains.

How then did the folding arise?

If we cut a section across the Aleutian Islands perpendicular to the chain and the parallel trench lying to the south, we shall have a figure something like that shown in figure 1 of the following plate. Now in the paper on the "Cause of Earthquakes" (§ 16) we have shown how the undermining of the sea bottom sinks the trough down deeper and deeper, and as the expulsion of lava continues it eventually becomes easier to fold up the side of the trough towards the ocean (at *b*) and make another range of mountains parallel to the first. And there is nothing to prevent the process from being repeated several times. When several successive ranges of mountains are thus developed in the process of expulsion under the margin of the sea, it is easy to see that the central range may finally be driven upward and flared out at the top exactly as in the Alps. Thus all this movement occurs in the sea, and eventually the range becomes like that now seen in Switzerland, as depicted by Heim, of Zürich.

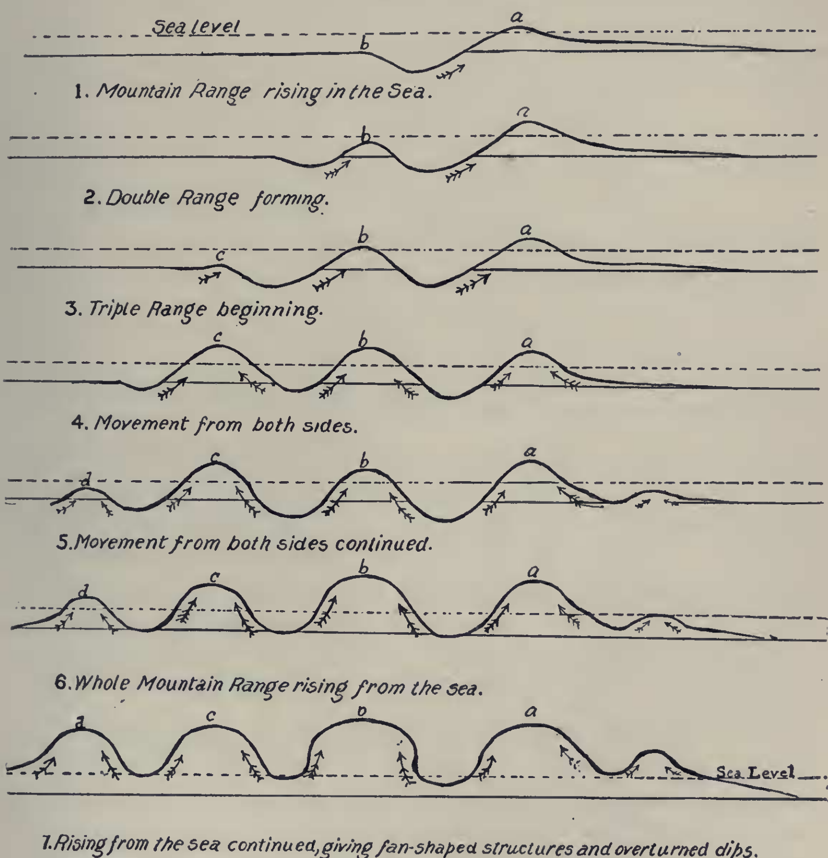

FIG. 11. Illustration of Formation of Complex Range, such as the Swiss Alps. The bending of the crust has caused it to pull apart at the top and bottom of the folds, where it is largely covered by sedimentary deposits and filled by molten rock from beneath, so that the breaks do not show at the surface, unless erosion has laid bare parts of the underlying structure. In these figures the thickness of the crust is less than half the width of the folds; and for clearness the depth of the sea is exaggerated.

As the movement continues the central range rises upwards, while its flanks sink down on either side, and thus the fan-shaped structure develops, so as to give overturned dip and inversion of strata once deposited horizontally in the bed of the sea.

This is a perfectly simple and direct explanation of one of the most mysterious phenomena heretofore encountered by naturalists.

The new theory of mountain formation is proved to represent a real law of nature by phenomena now witnessed in the Aleutian Islands, Japan and elsewhere. The fact that it perfectly accounts for the perplexing phenomena seen in the Swiss Alps, shows that they too were formerly under the sea, and were uplifted by the same force now at work in the Aleutian Islands and the Antandes.

Accordingly it is not remarkable that Professor Suess should, without knowledge of the *true cause,* describe the uplift of the Alps from the sea in words which are almost prophetic ("Face of the Earth," Vol. II, p. 552):

> "As a result of *tangential thrusts,* the sediments of this Sea (Mediterranean) were folded together and driven upward as a great mountain range, and the Alps have therefore been described as a compressed sea."

Without overestimating the significance of this result, it seems clear that neither parallel ranges nor fan-shaped structures with inverted dips will hereafter present any further difficulty to the geologist. Now that the true laws of such phenomena are known, it will be exceedingly interesting to work out the details of all the great mountain systems with which the earth is adorned.

§ 29. *All Complex Folding now seen in Mountain Ranges Originated in the Sea.*—It is scarcely necessary to add that all the complex folds now seen in mountain ranges were produced in the sea by the repetition of trenches dug out by earthquakes. The folds were frequently broken apart at both top and bottom, by the earthquake movements, and thus the folded crust is not shortened by anything like so much as has been supposed. Moreover where the fan-shaped structures and overturned dips appear, the two sides were never joined together by an arch above, as represented in the above figures by Heim, but were quite separated before the range arose to any considerable height. Accordingly it follows that erosion has not worn off anything like so much of the top of the range as the theory of a rounded arch would require. Thus we may not only explain the folds of the Alps, but also recognize that the folds both above and below were less extensive than was formerly supposed; and this greatly simplifies the labor of the geologist in restoring the former structure of mountain chains as they appeared before they were greatly eroded.

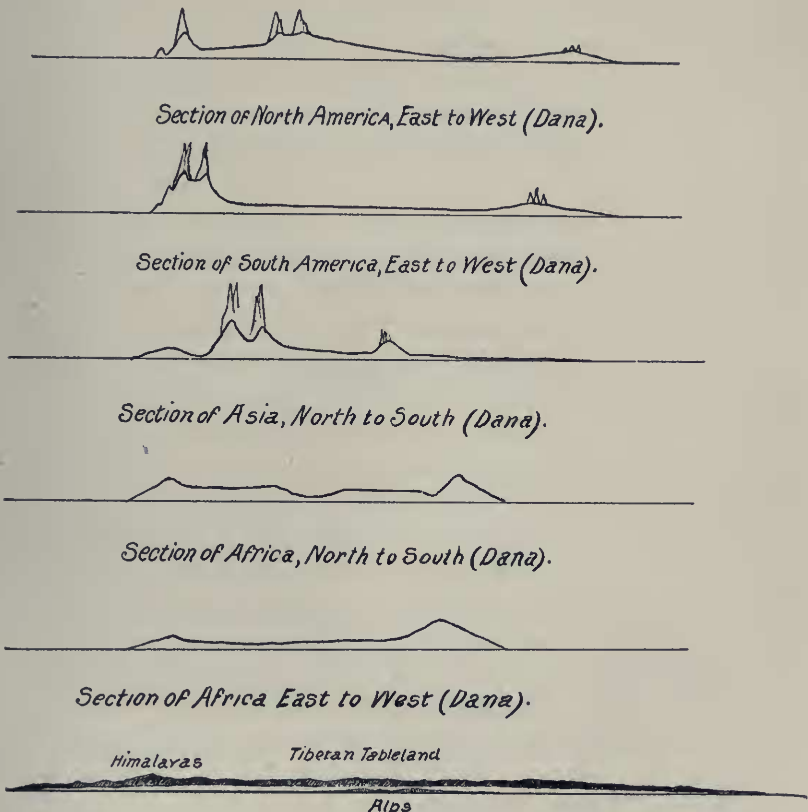

FIG. 12. Sections of the Continents, and of the Alps and Himalaya on the same Scale. (Gen. Strachey.)

The process of undermining the sea bottom in the expulsion of lava arising from the leakage of the ocean, has given rise to all the important folds of the earth's crust. Thus arose all the complicated folds in the Alps, Andes, Alleghenies and other mountain ranges. And wherever we see these folds sea trenches once existed, and the crust was pushed hither and thither by earthquakes, raising ridges and undermining the troughs, till the rocks were crumpled and folded as we find them to-day. *The simplicity of this cause, and the easy way in which we pass from the living troughs now being dug out in the sea to fossil troughs long since dead and now far inland give a genuine paleontological interest to the science of mountain formation.* What has long been mysterious and nearly inexplicable is now as clear as any theorem in geometry.

§ 30. *Application of the New Theory to the Allegheny Mountains.*—The Allegheny Mountains in Pennsylvania and Virginia are very remarkable for the great extent of the folds, and it seems worth while to dwell a moment on the mode by which these folds were produced. We have seen that they all arose in the sea, and by a repetition of the earthquake process of digging out trenches along the ancient shore line. As we shall see in Part V, § 41 of this paper, Professor James Hall so long ago as 1857 announced to the American Association in session in Montreal that the enormous thickness of the formations along the Appalachian Chain in the United States was due to the prolonged accumulation of sediments over a sinking sea bottom, at the margin of the continent; where the marine currents allowed the material to deposit.

Obviously if sea trenches were dug out by earthquakes they would become the basins for the accumulation of a vast amount of detritus. And when several trenches were successively dug out in the sea bottom by earthquakes depending on the Atlantic, would not the resulting folds give us the Allegheny, Tuscarora and Blue Ridge Mountains of Pennsylvania and Virginia? The famous Shenandoah Valley in Virginia is nothing but an ancient sea trough; and Pennsylvania has many such valleys originally formed in the depths of the sea. This is clearly indicated by the beautiful parallelism of the mountain ranges.

It is noticeable that the sea trench south of the Aleutian Islands is remarkably straight, and one may easily predict that the ranges hereafter to be formed in the North Pacific Ocean will be remarkably parallel like those now seen in Virginia and Pennsylvania. Under the circumstances can any one doubt that the sea was once very deep near where the Blue Ridge stands to-day?

Excluding from consideration the crystalline belt on the east, Claypole estimated the shortening of the Appalachians in Pennsylvania at 46 miles. In the same way McConnell estimated that of the Laramide range in British America at 25 miles, and Leconte that of the Coast Range in California at from 9 to 12 miles. Corresponding estimates have been made for many other mountain ranges; but, for reasons already given in dealing with the origin of the Swiss Alps, § 28, these estimates are too large. The crust was broken apart at both top and bottom when the ranges were in the sea, and the folds heretofore assumed to be complete were never really so. Consequently no slack in the earth's crust is required to explain these folds; it was never loose from the globe and never moved horizontally, except when forced by earthquake movements proceeding from the underlying trenches in the sea bottom.

The undermining and folding of the crust has given the Appalachian Mountains in many places the aspect of a series of immense billows, running parallel, as if swept in by a vast disturbance of the sea. But not even seismic sea waves of the most imposing magnitude could approach the size of these gigantic folds, the origin of which heretofore has been so mysterious. The finding of a simple and natural explanation of *these great billows of the land* will be scarcely less interesting than the discovery of the cause of seismic sea waves. Both depend on earthquakes, though in very different ways. The land billows are cumulative products of an infinite series of seismic disturbances along the margin of the sea; the seismic waves are small in comparison, and result from a single disturbance of the sea bottom, made in process of shaping the vast billows of the land, which in all generations have appealed to the imagination of the painter, poet, and student of nature.

§ 31. *Analogy Between the Uplift of the Islands of Japan by the Movement from the Tuscarora Deep and of the Plateau of Tibet from the Indian Ocean.*—The uplift of the Islands of Japan now going on by the expulsions of lava from beneath the Tuscarora Deep is proved by the terrible earthquakes and seismic sea waves afflicting that region, as well as by the historical fact that the east coast of Japan is known to be rising from the sea. Perhaps in general the movement is slow and insensible, but occasionally earthquakes have produced large disturbances of the level. The nature of earthquake movement in expelling lava from under the sea is too well known to leave any doubt as to what is going on in Japan. And the theory is confirmed by the fact that if Nipon and Yezo were dug off and thrown into the Tuscarora Deep they would about fill up that profound abyss and leave the sea of average depth.

Now there is a certain analogy between the uplift of these Japanese Islands, which are considerable areas, by the Pacific, and of the Plateau of Tibet by the Indian and Pacific oceans combined. Undoubtedly the valleys of the Indus, Ganges and Brahmaputra are the relics of ancient sea troughs which largely produced the Himalayas and the great plateau of Tibet. How much these troughs have been modified in later geological times we cannot estimate; but even now enough remains to tell the true story of Himalayan development. This is also indicated by the preservation of the earthquake belt south of the Himalayas. The meaning of these valleys and earthquake belts admits of no possible doubt. Just as the whole island of Nipon is being raised by movements from the Tuscarora Deep, so the whole of the Plateau of Tibet was once raised by an Indian Deep, of which these valleys are the remains.

In the same way the Valley of the Po is the remains of the sea valley which was most influential in uplifting the Swiss Alps. But in the case of the Alps, Geikie has shown that there was also a sea on the north, which has now quite disappeared, though traces of its former existence still remain.

§ 32. *The Origin of Volcanoes and the Conditions of their Maximum Development.*—It appears from the line of proof developed in this theory that volcanoes may break forth in any region near the sea where there are severe earthquake disturbances, by which the crust of the globe is sufficiently cracked to afford a vent for the steam imprisoned beneath. Now such vents are greatly facilitated in a chain such as the Aleutian Islands, in which the crumpling is extreme, and the expulsion of lava from beneath the sea rapid and violent. The crumpling breaks the crust along many lines, and as the earthquakes due to the expulsion of lava are both frequent and terrible, the chance of steam breaking through to the surface is much greater than in regions less wrinkled and less afflicted by earthquakes. The crust in the Andes was once folded by the sea in the same way as that in the Aleutian islands, and from this circumstance arises the violence of the volcanic outbreaks noticed all along the west coast of South America. From the great similarity of the volcanic phenomena in the Andes and in the Aleutian Islands, and its enormous prominence in both ranges, it seems obvious that we have here the conditions for its maximum development.

Charles Darwin believed that volcanoes usually break out in regions of elevation. No doubt this is true, for mountain ranges are the most conspicuous of rising areas. And according to this theory the tendency to rupture the crust is a maximum, when the ranges are being both folded and raised from the sea. Thus while some volcanoes may break out in less fractured regions of the earth's crust, the greatest volcanic activity develops where mountains are being formed in the sea, as in the Aleutian Islands. This view also enables us to understand why many volcanoes in the Andes are now extinct, though they were formerly active for immense periods of time, as we know from the thick deposits of volcanic debris and the immense height of the cones built up of lava, ashes and cinders.

IV. Comparison of the New Physical Theory of Mountain Formation Depending on the Leakage of the Oceans with the Theory of Secular Cooling and Contraction Heretofore Held by Men of Science.

§ 33. *General Remarks on the Method of Comparison Adopted.*—The new physical theory of mountain formation depending on the leakage of the oceans outlined in the three memoirs recently published by the American Philosophical Society and somewhat more fully developed in the present paper might seem incomplete if we failed to compare the new theory with the theory of secular cooling and contraction of the globe heretofore held by men of science generally. On several grounds an examination of the older theory can hardly fail to be instructive. And if this comparison of the older theory with that now adopted shall be the means of harmonizing in any considerable degree the divergent views heretofore prevailing, and of showing *that there is no important geological phenomenon which the new theory does not explain in a more simple and direct manner than the old theory,* such a comparison will no doubt seem quite justifiable. For it is highly desirable to establish the adequacy of the new theory to explain the *geological* as well as the *physical* phenomena noticed at the surface of the earth.

In making this comparison it is necessary to bear in mind that the geological data on many points are still very incomplete, and therefore we should expect agreement with the body of phenomena rather than with the details, about which much uncertainty still exists. Owing to the incompleteness of our knowledge of the mode of origin of the great mountain chains of the globe, the best plan of procedure seems to be: First, to give an exposition of the views of previous writers in regard to the individual great mountain systems; second, to add a résumé of the views of certain great geologists on mountain formation in general. Obviously such condensation of the views of others should wherever possible be given in their own words.

As this subject is extensive and widely scattered in a variety of publications, we must content ourselves with selecting those citations which seem of most interest, without in any way claiming to exhaust the subject. Indeed it may well be that some discussions of value will be entirely overlooked, but, as the theories have been but very little changed for many years, it is hoped that the following citations will be found adequate to give an intelligent grasp of the views heretofore accepted by the leading authorities. If there be those who doubt the propriety of including lengthy quotations from well-known authors, I must plead in extension of the course here adopted, that this memoir is intended for others besides geologists, and that all who are interested in the physics of the earth, whether they be mathematicians, astronomers, physicists, seismologists, geologists, or even chemists and biologists, are entitled to have a clear summary of the principal theories heretofore accepted in regard to the development of our globe. In dealing with a subject of such universal interest to all men of science, any reasonable condensation of the previous theories may be considered admissible, and one may have no hesitation in invoking the aid of many authors. If the establishment of a great law of nature may be thus facilitated, surely no one will doubt that the space utilized was devoted to a most useful purpose. The extreme specialization characteristic of the science of our day makes such summaries both useful and necessary for the intelligent study of great problems; and if more effort were made in this direction it might contribute materially to the progress of scientific research.

(A) Accounts of Particular Mountain Systems, and Their Supposed Mode of Development.

§ 34. *The Andes.*—We shall begin with the Andes of South America, because this is one of the largest, simplest and most typical of mountain systems; and if a theory will not explain the Cordilleras, we may despair of its explaining the more complicated mountains of the globe. The reader should carefully bear in mind not only what the author in question says from his own point of view, but also how the facts he mentions accord with the new theory developed in this paper.

In the *Encyclopedia Britannica,* ninth edition, under the article "Andes," we find the following lucid exposition of Andean development. It is not signed, but is supposed to have passed under the review of Sir Archibald Geikie.

"The formation of the Andes is due to several causes operating at distinct intervals of time. They consist mainly of stratified material which has been more or less altered. This material was deposited at the bottom of a sea, so that at some former time the highest portions were submerged, probably in consequence to a certain extent, of subsidence of the sea bottom. Since the latest deposits there has been upheaval and denudation. The range, then, has resulted from the accumulation of sediment on a subsiding area; from the subsequent upheaval of such deposits, which have been increased in height by the ejection of volcanic products; and from the operation of denuding agents.

"As far as our present knowledge goes, it appears to be probable that the Andes mark an area on which sedimentary deposits have been accumulated to a greater thickness than on any other portion of South America. It is further demonstrable that these deposits belong to several geological periods, the elevation having occurred at different periods, while their axes extend in different directions. Hence it is a complex range of mountains formed by the combination of several distinct systems of ridges. The width of the range varies from about 60 to 300 or more miles, but, as compared with other mountains, the Andes are for the most part narrow relatively to their height. Where their special features are most characteristically developed, they consist of a massive embankment-like foundation, rising with a rapid slope from the low country on either side, and having its margins surmounted by lofty ridges of ragged or dome-like summits. These Cordilleras, as they are usually termed, flank longitudinal valleys, or plain-like depressions which form the highest levels of the central portion of the gigantic embankment, and which vary in width from twenty to sixty miles. At intervals the longitudinal depression is broken up, either by ridges connecting the Cordilleras, or by lofty plateau-like uplands. In several cases these transverse ridges and belts of high ground form the main watershed of the country. They are rarely cut across by the river systems, whereas both the marginal Cordilleras are intersected at numerous points, and more especially by the rivers draining the eastern slope of the country. In no case do these eastern rivers originate to the west of the western Cordilleras. A few of the central valleys, or plain-like depressions, have no connection either with the western or eastern river system. Roughly speaking the height of the central plains or valleys is from 6000 to 11,000 feet above the sea; of the passes and knots, from 10,000 to 15,000 feet; and of the highest peaks, from 18,000 to 23,290 feet—the last being the altitude of Aconcagua in Chili, which is generally considered to be the highest peak in America. Judging from these estimates, we may regard the bulk of the Andes as somewhere about that of a mass 4400 miles long, 100 miles wide, and 13,000 feet high, which is equivalent to 5,349,801,600,000,000 cubic feet. On this basis we find that the Mississippi would carry down an equivalent mass of matter in 785,000 years. The rate of denudation in certain river basins varies from one foot in 700 years to one foot in 12,000 years. Assuming that similar rates would apply to the Andes, they would be denuded away in from 9 to 156 million years. In all probability, much less than 9 million would suffice. On the other hand the Andes would be swept away in 135,000 years, supposing the denuding powers of the globe were concentrated on them alone. From the above data, and assuming the average specific gravity of the matter forming the Andes to be 2.5, the weight of the portion above the sea may be estimated at 368,951,834,482,750 tons, giving an average of about 1,000 tons on each square foot at the level of the sea. Under Aconcagua the pressure would be about 1,780 tons per foot at the same level, provided, of course, it were not, as it no doubt is, more or less modified by lateral pressure. These figures afford some, though at best a vague, conception of the mighty grandeur of this range of mountains, and of the scope there is for the exertion of enormous pressure. How vast then, must be those forces which have counteracted such pressures, and upheaved the ocean-spread sediments of the continents, until the Andes, that

'giant of the Western Star,
Looks from his throne of clouds
O'er half the world!'

But, however vast the Andes may seem to us, it should be remembered that they form but an insignificant portion of the globe itself. Aconcagua is about 1/2,000 of the earth's diameter, which is relatively not more than a pimple 1/30 of an inch high on the skin of a tall man." (Ency. Brit., Vol. II, pp. 15–16.)

The account here given of how the Andes were formed seems exceedingly instructive. In the sea troughs formerly existing between the ocean and the eastern range, which was the first thrown up, we have a complete explanation of the extraordinary depth of sedimentation; for in such trenches adjacent to a new range the rate of sedimentation would be a maximum. The subsequent uplifting of the western side of the sea troughs, with the vast lateral folding and compression necessarily accompanying this movement, accounts for the plateaus, valleys and general structure of the Andes, as well as for the violent volcanic outbreaks, which are said to greatly predominate in the range nearest the sea, from which the expulsion of lava giving rise to this mighty Cordillera proceeded. The vastness and height of the Andes and the terrific forces operating to erect this gigantic wall along the shore of the continent is a true measure of the secular leakage of the Pacific Ocean, and of the automatic relief it finds by folding the earth's crust along the border, in the countless successive expulsions of lava from beneath the bed of the sea. It is needless to point out how perfectly the new theory explains the persistence of the earthquake belt along the western shore of South America, and of the seismic sea waves by which that region is so often afflicted. It is obvious that the forces which uplifted the mountain also carried up the plateaus enclosed between the various ranges.

§ 35. *The Himalayas.*—The following luminous account of the Himalayas by the late Lieutenant General Sir Richard Strachey, *Encyclopedia Britannica,* article "Himalayas," is of extreme interest. General Strachey resided in India for many years, and made a life long study of the Geology and Geography of Central Asia. He was the principal authority of his time on this little explored continent and died February 12, 1908, at the age of 91 years.

"Scientific investigation has clearly shown that, so far as the main characteristics of the mountains are concerned, the natural boundaries of the Himalayan system must be carried much farther than had at first been recognized. Considerable obscurity still involves the eastern portion of these mountains, and there is great want of precise knowledge as to their connection with the ranges of western China, from which are thrown off the great rivers of China, Siam, and Burmah. On the west, however, it has been completely established that a continuous chain extends beyond the Indus along the north of the Oxus, and ends in that quarter about 68° E. long. In like manner it is found that no separation can be established, except a purely arbitrary one, between the Himalaya as commonly defined and the greatly elevated and rugged table-land of Tibet; nor between this last and the mountain ranges which form its northern border along the low-lying desert regions of central Asia.

"It thus appears that the Himalaya, with its prolongation west of the Indus, constitutes in reality the broad mountainous slope which descends from the southern border of the great Tibetan table-land to the lower levels of Hindustan and the plains of the Caspian; and that a somewhat similar mountain face, descending from the northern edge of the tableland, leads to another great plain on the north, extending far to the eastward, to the northern borders of China. Towards its northwest extremity this great system is connected with other mountains—on the south, with those of Afghanistan, of which the Hindu-Kush is the crest, occupying a breadth of about 250 miles between Peshawur and Kunduz; and on the north, with the mountains that flank the Jaxartes or Sir on the north, and the Thian-shan or Celestial Mountains. The eastern margin of Tibet descends to western China, and the south-eastern termination of the Himalaya is fused into the ranges which run north and south between the 95th and 100th meridians, and separate the rivers of Burmah, Siam, and western China.

"Nor can any of the numerous mountain ranges which constitute this great elevated region be properly regarded as having special, definite, or separate existence apart from the general mass of which they are the component parts; and Tibet cannot be rightly described, as it has been, as lying in the interval between the two so-called chains of the Himalaya and the Kouenlun or Kara Koram. It is in truth the summit of a great protuberance above the general level of the earth's surface, of which these alleged chains are nothing more than the south and north borders, while the other ranges which traverse it are but corrugations of the mass more or less strongly marked and locally developed.

"The average level of the Tibetan tableland may be taken at about 15,000 feet above the sea. The loftiest points known on the earth's surface are to be found along its southern or Himalayan boundary; one of them falls very little short of 30,000 feet in elevation, and peaks of 20,000 feet bound the entire chain. The plains of India which skirt the Himalayan face of the tableland, for a length of rather more than 1,500 miles, along the northern border of British India, nowhere rise so much as 1,000 feet above the sea, the average being much less. The low lands on the north, about Kashgar and Yarkend, have an elevation of from 3,000 to 4,000 feet, and no part of the Central Asiatic desert seems to fall below 2,000 feet, the lake of Lob-nor being somewhat above the level. The greatest dimension of the Tibetan mountain area from east to west may be about 2,000 miles, while its average breadth somewhat exceeds 500 miles; about 100 miles on either side constitute the sloping faces, the central tableland having a width of about 200 miles on the west and probably 500 miles at its eastern border."

General Strachey thus shows that the Himalayan mountains and Tibetan Plateaus are directly and intimately connected as merely different parts of one great continuous movement of the earth's crust.

After describing many features of the Himalayas, General Strachey continues:

"The general conclusion that may be drawn from the facts of structure thus briefly indicated is that the elevation of the Himalaya to its present great height is of comparatively recent occurrence. An area of land must have existed where the main line of snowy peaks now stands, which has not been submerged since the Palæozoic period, and which then had its northern boundary somewhere along what has been termed the Indian watershed. Evidence of a similar ancient sea on the south also exists, but in less definite shape; and whether it was united with the northern sea or not is still a matter of conjecture, though the distinctive character of the fossils rather indicates that there was no direct union. The possible connection of this ancient Himalayan land area with the pre-Tertiary land of the peninsula of India is also only a matter for speculation.

"There is further reason to infer that the existence of the great line of peaks is rather due to some previous line of elevation on the ancient land, which has continued to retain its relative superiority while the whole areas have been raised, rather than to any special line of energy of upheaval of recent date; and that the fundamental features of its former configuration of surface in mountain and valley have been preserved throughout. There is evidence for the conclusion that the chief rivers of the pre-Tertiary land issued from the mountains where the present main streams are found, and this embryo Himalaya may have been of such moderate height as to have permitted the passage across it of the Siwalik mammals, the remains of which appear both on the border of the Indian plain and in Tibet. It is after the middle Tertiary epoch that the principal elevation of these mountains must have taken place, and about the same time also took place the movements which raised the tablelands of Afghanistan and Persia, and gave southern Asia its existing outlines.

"The best answer that can be given to an inquiry as to how changes of level could have arisen, such as those which are observed in the Himalaya, is that they should be regarded as due rather to secondary actions consequent on the general contraction of the cooling terrestrial sphere than to direct elevating forces, for which no known origin can be assigned. The contraction of the cooling but now solid crust of the earth must have set up great horizontal strains, partly of tension and partly of compression which would necessarily have been followed by rupture or crushing along lines of least resistance, and the movements on such lines are marked by the great mountain ranges that traverse the surface. A dislocation of the solid crust of the earth once having taken place, it would probably continue to be a line of least resistance ever after, and a succession of movements during past geological periods may thus be reasonably expected along such lines. Somewhat in proportion as the disturbing forces are intense, and the thickness of the crust on which they act is great, will be the tendency of the lines of rupture to be continuous for a considerable distance; and as the disturbed area is extended in its dimensions, the probability will increase of a repetition of a series of similar dislocations on lines approximately parallel to, or at right angles to, one another and to the line on which the greatest compression and consequent tension take place. In a disturbed area, one transverse dimension of which is sensibly greater than the rest, the longitudinal ruptures will predominate in the interior and the transverse towards the borders. Almost all mountains give indications of having been shaped by forces thus related, and to the action of such forces may the main characteristics of the structure of the Himalaya, and the arrangement of its ridges and valleys be attributed. Whatever may be the power of rivers in general as instruments of erosion, and whatever effect the Himalayan rivers have had in removing the fragments of the rocks over and among which they took their courses, it is hardly possible to doubt that their main directions were determined by the anterior lines of dislocation which opened up hollows down which they could flow, and which must invariably have been accompanied by a destructive and crushing action on the rocks along them, which has enabled the waters the more readily to sweep away the obstacles in their path. The parallelism of many of the great Tibetan and Himalayan rivers for hundreds of miles together, and such mountains, seems wholly inexplicable in any other manner." (Ency. Brit., p. 828.)

This account is quite clear and satisfactory, except that part of it which deals with the cooling and contraction of the globe. Here General Strachey has made the best of a very inadequate hypothesis.

Just as the Andes were formed by expulsions of lava from under the Pacific, so also here the Himalayas were formed by a corresponding movement due mainly to the Indian Ocean, which has also raised high mountains along the eastern border of Africa. We cannot yet give all the details of the Himalayan development, but in general it is evident that it was similar to that of the Andes. The uplift of the great plateau of Tibet corresponds to that of Titicaca. And the parallel ranges of the Himalayas originated by the usual process of the folding up of successive sea trenches. On the outside of these mountains there still remain trough-like depressions where the Indus, Ganges and Brahmaputra now flow. The undermining produced in raising the Himalayan embankment still shows in the valleys to the south, though the sea has receded; and the great earthquake belt south of the Himalayas still discloses to us the nature of the forces which produced this mighty uplift.

The following critical passages by General Strachey are also of decided interest:

"The great peaks are, with few exceptions, composed of schistose rock, though granite veins may be seen in the mountain faces to very great elevations; one of these exceptions is the great peak of Kamet in Kumaon, which rises to about 25,000 feet in what appears to be a mass of grey granite.

"Passing to the north of the line of great peaks the metamorphosed schists are suddenly replaced by slates and limestones, which are in many places highly fossiliferous, exhibiting what appears to constitute in the aggregate a fairly continuous series from the Lower Silurian to the Cretaceous formations, though the complete sequence has not been observed in any one locality. The western region of the Himalaya alone has been sufficiently explored to admit of any positive statements, but the indications gathered from such imperfect accounts and other data as exist relative to the eastern parts of the mountains leave little doubt that the change observed in the west on approaching and entering Tibet holds good on the east also, and that the general physical features of the whole tract are much alike, though doubtless with many differences in detail.

"The fossiliferous strata of western Tibet are continued, though perhaps with some breaks, to the Tertiary period. In certain localities nummulitic rocks, probably Eocene, have been observed, and from the great alluvial deposit which forms the plain of Gugé, already noticed, the remains of mammals, apparently of Siwalik age, have also been obtained. Among these were bones of the elephant and rhinoceros, the existence of which, in the present condition of these regions, would be wholly impossible; so that there is no room to doubt that these deposits have been raised from a comparatively low level to their existing great elevation of upwards of 15,000 feet, since they were laid out. As in the case of the plain of India, we here, too, have no complete proof of the origin of these great nearly horizontal deposits, but it seems clear, from the materials of which they are formed, that they must have been laid out by the water, either by the sea or some great inland lake. They are largely composed of boulder deposits, and large boulders are strewed over the surface imbedded in the ground in a manner that seems only explicable as the result of the action of a considerable body of water.

"Several lines of granitic and eruptive rock occur in western Tibet, of which all that need here be said is that they appear all to be older than the Tertiary alluvium, but some of them are possibly contemporaneous with the nummulitic and older formations." (Ency. Brit. p. 828.)

In an earlier passage, after comparing some of the smaller Himalayan ranges to the Swiss Alps, General Strachey adds:

"To obliterate these two ranges from the Himalaya would make no very sensible inroad on it, though they surpass in bulk the whole of the Swiss Alps; and it is no exaggeration to say that, along the entire range of the Himalaya, valleys are to be found among the higher mountains into which the whole Alps might be cast without producing any result that would be discernible at a distance of ten or fifteen miles. And it is important to bear in mind these relations of magnitude, for the terms at our disposal in the description of the mountains are so limited that it is necessary to employ the words chain, range, ridge, spur, etc., rather with reference to relative than to absolute importance, so that the scale of our nomenclature changes with the extent and altitude of the mountains of which we speak." (Ency. Brit., p. 827.)

§ 36. *The Alps.*—In the *Enclycopedia Britannica,* article "Alps," by John Ball, we find the following brief outline of the salient features:

"Accurate knowledge of the Alps is so recent that few attempts have been made to establish a general division of the entire region, and it cannot be said that any one arrangement has obtained such general recognition as not to be open to future modification; but there is a pretty general agreement as to the main features of that here proposed, to which a few general remarks must be premised.

"Whatever may have been the original cause of the disturbances of the earth's crust to which great mountain chains owe their existence, it is generally, though not universally, true that the higher masses (formed of crystalline rock and geologically more ancient) are found towards the central part, and that these are flanked by lower ranges, composed of more recent rocks, which surround the central groups very much as an outer line of entrenchment may be seen to surround a fort. In most cases it is not possible to descend continuously in a nearly direct line from the crest of a great mountain chain to the plains on either side, for there are usually intermediate valleys, running more or less parallel to the central range, which separate this from outer secondary ranges. These in turn, are often accompanied by external ranges, intermediate between them and the plains, and related to them as they are to the central ranges. The type of arrangement here described is more or less traceable throughout the greater part of the Alps, but is most distinctly exhibited in the eastern portion lying between the Adige and the frontier of Hungary. We have a central range, composed mainly of crystaline rock; a northern range, formed of secondary rocks, separated from the first by the great valleys of the Inn, the Salza, and the Enns; a southern range, somewhat similar to the last in geological structure, divided from the central one by the Rienx, or east branch of the Adige, and the Drave. Flanking the whole, as an external entrenchment on the north side, are the outer ranges of the Bavarian Alps, of the Salzkammergut, and of Upper Austria, to which corresponds on the south side the Monti Lessini, near Verona, the mountains of Recoaro, those of the Sette Comuni, and the considerable masses crowned by the summits of the Grappa, the Col. Vicentino, the Monte Cavallo, the Monte Matajur, and Monte Nanos. Where, as in the case above mentioned, the secondary ranges of the Alps rise to a greater altitude, and are completely separated from the neighbouring portions of the central chain, it is impossible not to distinguish them as distinct groups; but the outermost ranges, which rarely rise above the forest zone, are in all cases regarded as appendages of the adjoining groups. These outer ranges are called in German Voralpen, and in Italian Prealpi." (Ency. Brit., p. 623.)

Again on page 620, this author remarks:

"In every mountain system geographers are disposed to regard the watershed, or boundary dividing the waters flowing towards the opposite sides of the range, as marking the main chain; and this usage is often justified by the fact that the highest peaks lie on, or very near, the boundary so defined. In applying this term in the case of the Alps, there are, however, difficulties arising from their great extent and the number of their branches and ramifications. Many of the loftiest groups lie altogether on one side of that which we call the main chain, and at the eastern extremity, where all drainage is ultimately borne to the Black Sea, we must be partly guided by geological considerations in deciding which of several ranges deserves to be considered pre-eminent." (Vol. I., p. 620.)

Sir Archibald Geikie's discussion of the origin of the Alps, in the article "Geology," *Encyclopedia Britannica* (pp. 373-374), bears on the problem now before us:

"The Alps, on the contrary, present an instructive example of the kind of scenery that arises where a mass of high ground has resulted from the intense corrugation and upheaval of a complicated series of stratified and crystalline rocks, subsequently for a vast period carved by rain, frost, springs and glaciers. We see how, on the outer flanks of those mountains among the ridges of the Jura, the strata begin to undulate in long wave-like ridges, and how, as we enter the main chain, the undulations assume a more gigantic tumultuous character, until, along the central heights, the mountains lift themselves towards the sky like the storm-swept crests of vast earth billows. The whole aspect of the ground suggests intense commotion. Where the strata appear along the cliffs or slopes they may often be seen twisted and crumpled on the most gigantic scale. Out of this complicated mass of material the sub-aerial forces have been ceaselessly at work since its first elevation. They have cut valleys, sometimes along the original depressions, sometimes down the slopes. They have eroded lake-basins, dug out corries or cirques, notched and furrowed the ridges, splintered the crests, and have left no part of the original surface unmodified. But they have not effaced all traces of the convulsions by which the Alps were upheaved."

In his account of the Miocene ("Text-book of Geology," p. 1261, edition of 1903), Geikie says:

"The Gulf of Gascony then swept inland over the wide plains of the Garonne, perhaps even connecting the Atlantic with the Mediterranean by a strait running along the northern flank of the Pyrenees. The sea washed the northern base of the now uplifted Alps, sending, as in Oligocene time, a long arm into the valley of the Rhine as far as the site of Mainz, which then properly stood at the upper end, the valley draining southward instead of northward. The gradual conversion of salt into brackish and fresh water at the head of this inlet took place in Miocene time. From the Miocene firth to the Rhine, a sea-strait ran eastwards, between the base of the Alps and the line of the Danube, filling up the broad basin of Vienna, sending thence an arm northwards through Moravia, and spreading far and wide among the islands of southeastern Europe, over the regions where now the Black Sea and Caspian basins remain as the last relics of this Tertiary extension of the ocean across southern Europe. The Mediterranean also still presented a far larger area than it now possesses, for it covered much of the present lowlands and foot-hills along its northern border, and some of its important islands had not yet appeared or had not acquired their present dimensions."

On pages 1371-2 of Geikie's "Geology," we find the following interesting passages:

"*Alpine Type of Mountain Structure.*—It is along a great mountain chain like the Alps that the most colossal crumplings of the terrestrial crust are to be seen. In approaching such a chain, one or more minor ridges may be observed running on the whole parallel with it, as the heights of the Jura flank the north side of the Alps, and the sub-Himalayan hills follow the southern base of the Himalayas. On the outer side of these ridges, the strata may be flat or gently inclined. At first they undulate in broad gentle folds; but traced towards the mountains these folds become sharper and closer, their shorter sides fronting the plains, their longer slopes dipping in the opposite direction. This inward dip is often traceable along the flanks of the main chain of mountains, younger rocks seeming to underlie others of much older date. Along the north front of the Alps, for instance, the red molasse is overlain by Eocene and older formations. The inversions and disruptions increase in magnitude till they reach such colossal dimensions as those of the Glärnisch, where pre-Cambrian schists, and Triassic, Jurassic, and Cretaceous rocks have been driven for miles over the Eocene and Oligocene flysch (pp. 677, 693). In such vast crumplings and thrusts it may happen that portions of older strata are caught in the folds of later formations, and some care may be required to discriminate the enclosure from the rocks of which it appears to form an integral and original part. Some of the recorded examples of fossils of an older zone occurring by themselves in a much younger group of plicated rocks may be thus accounted for.

"The inward dip and consequent inversion traceable towards the center of a mountain chain lead up to the fan-shaped structure (p. 678) where the oldest rocks of a series occupy the center and overlie younger masses, which plunge steeply under them. Classical examples of this structure occur in the Alps (Mont Blanc, Fig. 258, St. Gothard), where crystalline rocks such as granite, gneiss, and schists, the oldest masses of the chain, have been ridged up into the central and highest peaks. Along these tracts, denudation has been of course enormous, for the appearance of the granitic rocks at the surface has been brought out, not necessarily by actual extrusion into the air, but more probably by prolonged erosion, which in these higher regions, where many forms of sub-aerial waste reach their most vigorous phase, has removed the vast overreaching cover of younger rocks under which the crystalline nucleus doubtless lay buried."

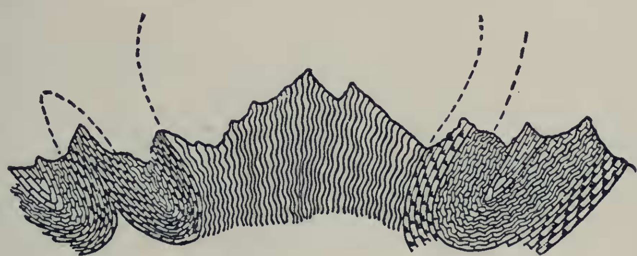

FIG. 13. Fan-shaped Structure, Central Alps.

Again on page 1372, we read:

"A mountain chain may be the result of one movement, but probably in most cases is due to a long succession of such movements. Formed on a line of weakness in the crust, it has again and again given relief from the strain of compression by undergoing fresh crumpling and upheaval. Successive stages of uplift are usually not difficult to trace. The chief guide is supplied by unconformability. . . .

"In most great mountain chains, however, the rocks have been so intensely crumpled, dislocated, and inverted, that much labor may be required before their true relations can be determined.

"The Alps offer an instructive example of a great mountain system formed by repeated movements during a long succession of geological periods. The central portions of the chain consist of gneiss, schists, granite, and other crystalline rocks, partly referable to the pre-Cambrian series, but some of which (Schistes lustrés, Bündnerschiefer) include metamorphosed Palæozoic, Secondary, and in some places, perhaps, even older Tertiary deposits (pp. 802, 1099). It would appear that the first outlines of the Alps were traced out even in pre-Cambrian times, and that after submergence, and the deposit of Palæozoic formations along their flanks, if not over most of their site, they were reelevated into land. From the relations of the

Mesozoic rocks to each other, we may infer that several renewed uplifts, after successive denudations, took place before the beginning of Tertiary times, but without any general and extensive plication. A large part of the range was certainly submerged during the Eocene period under the waters of the wide sea which spread across the center of the Old World, and in which the nummulitic limestone and flysch were deposited. But after that period the grand upheaval took place to which the present magnitude of the mountains is chiefly due. The older Tertiary rocks, previously horizontal under the sea, were raised up into mountain-ridges more than 11,000 feet above the sea-level, and together with the older formations of the chain, underwent colossal plication and displacement. Enormous slices of the oldest rocks were torn away from the foundations of the chain and driven horizontally for miles until they came to rest upon some of the newest formations. The thick Mesozoic groups were folded over each other like piles of carpets, and involved in the lateral thrusts so as now to be seen resting upon the Tertiary flysch. So intense was the compression and shearing to which the rocks were subjected that lenticles of the Carboniferous series have been folded in among Jurassic strata, and the whole have been so welded together that they can hardly be distinguished where they meet, and what were originally clays and sands have been converted into hard crystalline rocks. It is strange to reflect that the enduring materials out of which so many mountains, cliffs, and pinnacles of the Alps have been formed are of no higher geological antiquity than the London Clay and other soft Eocene deposits of the south of England and the north of France and Belgium. At a later stage of Tertiary time, renewed disturbance led to the destruction of the lakes in which the molasse had accumulated, and their thick sediments were thrust up into large broken mountain masses, such as the Rigi, Rossberg, and other prominent heights along the northern flanks of the Alps. Since that last post-Eocene movement, no great orogenic paroxysm seems to have affected the Alpine region. But the chain has been left in a state of unstable equilibrium. From time to time normal faults have taken place whereby portions of the uplifted rocks have sunk down for hundreds of feet, and some of these dislocations have cut across the much older and more gigantic displacements of the thrust-planes (Fig. 282). At the same time continuous denudation has greatly transformed the surfaces of the ground, so that now cakes of gneiss are left as mountainous outliers upon a crushed and convoluted platform of Tertiary strata. Nor, in spite of the settling down of these broken masses, has final stability been attained. The frequent earthquakes of the Alpine region bear witness to the strain of the rocks underneath, and the relief from it obtained by occasional rents propagated through the crust along the length of the chain."

In view of the explanation of the folding of the Alps given in § 28, we need not comment on these views. They confirm the theory outlined in this paper, that the plications of all such chains must be sought in the actions of the sea, and mainly while the range is under water, and not at all in the secular cooling of the globe.

V. Comparison of the Old and New Theory of Mountain Formation Continued.

(B) Views of Eminent Geologists on Mountain Formation in General.

§ 37. *Elie de Beaumont's Theory of the Secular Cooling and Collapse of the Globe.*—This venerable theory is thus condensed by Lyell:

"The origin of these chains depends not on partial volcanic action or a reiteration of ordinary earthquakes, but on the secular refrigeration of the entire planet. For the whole globe, with the exception of a thin envelope, much thinner in proportion than the shell to an egg, is a fused mass, kept fluid by heat, but constantly cooling and contracting in dimensions. The external crust does not gradually collapse and accommodate itself century after century to the shrunken nucleus, subsiding as often as there is a slight failure of support, but it is sustained throughout whole geological periods, so as to become partially separated from the nucleus until at last it gives way suddenly, cracking and falling in along determinate lines of fracture. During such a crisis the rocks are subjected to great lateral pressure, the unyielding ones are crushed, and the pliant strata bent, and are forced to pack themselves more closely into a smaller space, having no longer the same room to spread themselves out horizontally. At the same time, a large portion of the mass is squeezed upwards, because it is in the upward direction only that the excess in size of the envelope, as compared to the nucleus can find relief. This excess produces one or more of those folds or wrinkles in the earth's crust which we call mountain-chains."

De Beaumont's theory is given more from its antiquity than from its present day importance, and yet in some form it still holds its place in all our treaties on geology. Indeed the latest works include discussions of the strength of domes, as if the nucleus of the globe were shrinking away from the crust, and the latter thus subjected to crushing from its own weight.

§ 38. *Views of Lyell.*—This great geologist always rejected Elie de Beaumont's theories of mountain formation, and gave the most cogent reasons for his course. He adopted the theory that the land is occasionally depressed and elevated, by internal forces, but did not definitely decide what forces produced these progressive or oscillatory movements of the earth's crust. One of Lyell's greatest disciples was Charles Darwin, whose views we shall now very briefly recall.

§ 39. *Views of Charles Darwin.*—The views of Darwin are very briefly and lucidly set forth by Professor Suess ("Face of the Earth," Vol. I, p. 104), as follows:

"The earthquake of February 20, 1835 (at Conception, Chili), gave rise to one of the most important works on the elevation of mountains, indeed I may say to the the only attempt, based on direct observation of nature, to establish more exactly the older theories concerning the force which is supposed to have raised up mountain chains. The author of this work is Charles Darwin. Since that time no second attempt, or at least no attempt of equal importance, has been made in this direction. To day, more than half a century later, it is possible to hold other opinions on these questions and yet to recognize the boldness of the generalization which even then revealed the master.

"Darwin saw the awakening activity of the volcanoes during and after the earthquake; he believed he saw elevation, although not uniform elevation of the solid ground; in addition he saw the terraces along the coast. But he also knew that similar terraces occur on the east coast of South America, where there are no volcanoes and no earthquakes. The earthquakes must therefore have appeared to his eyes as the local expression of a universal force. The secular contraction of the earth, a theory already eagerly advocated by several investigators, Darwin justly held to be entirely unsuited to explain those intermittent elevations which the terraces betrayed, and thus he reached the conclusion:

"'That the form of the fluid surface of the nucleus of the earth is subject to some change, the cause of which is entirely unknown and the effect of which is slow, intermittent but irresistible.'"

§ 40. *Views of Professor James D. Dana.*—The views of this eminent geologist have been carefully discussed in the paper on "The New Theory of Earthquakes and Mountain Formation as Illustrated by Processes Now at Work in the Depths of the Sea," § 13. The reader is referred to that discussion. Here it must suffice to say that, although Dana recognized that there was a fundamental relationship between the depth and extent of an ocean and the height of the mountains which surround it, he was unable to define this relationship except in very general terms, and could not assign any definite cause for the law which he pointed out. He considered the oceanic basins as subsiding, while the continents were being elevated.

Though Dana's views were somewhat modified by later study and investigation, he always maintained that "the principal mountain chains are portions of the earth's crust which have been pushed up and often crumpled or plicated by lateral pressure resulting from the earth's contraction." In order to explain this supposed mode of action he held that the oceanic areas have been "the regions of greatest contraction and subsidence, and that their sides have been pushed like the ends of an arch, against the borders of the continents."

Even with these arbitrary assumptions it is not at all clear how the settlement of the Pacific Ocean could elevate our great plateau west of the Rocky Mountains, which is nearly a thousand miles wide. If the subsidence of the ocean bed had pushed up the margin of North America, the crumpling and elevation of the land could not well extend one third of the way across the continent. We need not, however, be greatly surprised at this difficulty, for at best Dana's theory is vague, and he evidently could not understand just how the elevation had come about. Yet so fully was Dana convinced of the dependence of the mountains on the oceans adjacent to them that he reduced it to calculation by the rule-of-three. He says:

"The relation of the oceans to the mountain borders is so exact that the rule-of-three form of statement cannot be far from the truth. *As the size of the Appalachians to the size of the Atlantic, so is the size of the Rocky chain to the size of the Pacific.* Also, *as the height of the Rocky chain to the extent of the North Pacific, so are the height and boldness of the Andes to the extent of the South Pacific.*" ("Manual of Geology," 1863, p. 25.)

This was indeed a remarkably near approach to the great law of nature, that the mountains along the coasts are formed by the expulsion of lava from under the sea, and are, therefore, everywhere proportional to extent and depth of the adjacent oceans.

§ 41. *Views of James Hall.*—In 1857 this distinguished American geologist announced in a presidential address to the American Association at Montreal, that the enormous depth of the sedimentation along the Appalachian chain was due to the prolonged accumulation of sediments along a sinking, off-shore line of sea bottom. He reached this view from the careful study of the

Appalachian and other American mountain regions. To explain such deposits he supposed that marine currents had formerly traversed these regions and by gradually depositing sediments of great weight had also sunk the crust till at length a great thickness was attained. When the rocks thus formed had become solidified and crystallized the borders of the continent were afterwards upraised somehow. He did not indicate how the uplift had come about, nor did he think that the mountain regions had been raised separately. Denudation had then commenced, and finally given the mountains the forms they have today.

Keferstein, Sir John Herschel, Dr. T. Sterry Hunt and others, along with Hall, or even before him, in some cases, had developed the theory of aqueo-igneous fusion, which was supposed to produce a plastic zone between the consolidated crust and the solid nucleus. This theory supposed that the isogeotherms rise in regions of heavy sedimentation. Hall held that this would

"cause the bottom strata to establish lines of weakness or of least resistance in the earth's crust, and thus determine the contraction which results from the cooling of the globe to exhibit itself in those regions, and along those lines where the ocean's bed is subsiding beneath the accumulated sediments."

Many of the views afterwards more fully developed by Leconte are here faintly traced by Hall, and for that reason these early views of mountain formation are worthy of attention.

§ 42. *Views of Leconte.*—This veteran geologist gave great attention to mountain formation throughout a long career, and his residence on the Pacific Coast gave him exceptional facilities for studying the ranges of our western states, and especially of California, which includes the most remarkable developments in North America. The views at which Leconte arrived, as set forth in his "Elements of Geology," edition of 1896, are as follows:

"*Mountain Origin.*

"Leaving aside for the present all disputed points, it is now universally admitted that mountains are not usually pushed up by a vertical force from beneath, as once supposed, but are formed wholly by *lateral pressure*. The earth's crust along certain lines is *crushed together* by lateral or horizontal pressure and rises into a mountain-range along the line of yielding, and to a height proportionate to the amount of mashing. But the yielding is not by rising into a hollow arch, nor into such an arch filled beneath with liquid (for in neither case would the arch support itself), but by mashing together and in thickening and crumpling of the strata and an upswelling of the whole mass along the line of greatest yielding. That this is the immediate or *proximate* cause of the origin or elevation of mountains is plainly shown by their structure. As to the *ultimate cause*—*i. e.*, the cause of the enormous lateral pressure—this lies still in the field of discussion. We shall discuss it briefly in its proper place" (pp. 261–2).

Again, on page 264, we find this account:

"*Proof of Elevation by Lateral Pressure alone: 1. Folding.*—It is evident that foldings such as those represented in all the above figures, and which occur in nearly all mountains, cannot be produced except by lateral pressure, and are therefore proof of such pressure. But, moreover, it can be shown that, when we take into consideration the immense thickness of mountain strata and the degree of folding, lateral pressure is *sufficient* to account for the whole elevation, without calling in the aid of any upward pushing from beneath. For example, the Coast range of California (Fig. 228) is composed of at least five anticlines and corresponding synclines. If

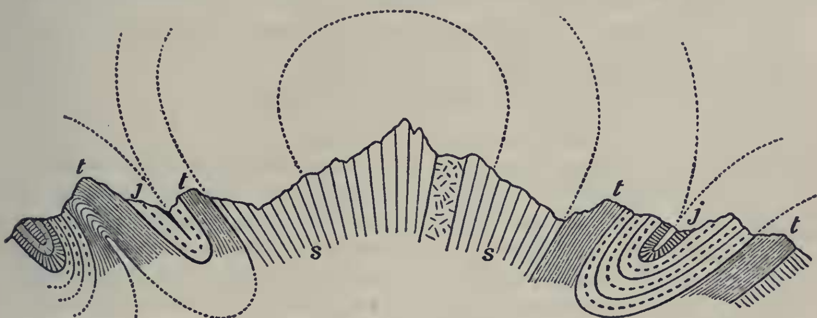

FIG. 14. Section of a Portion of the Alps.

its folded strata were spread out horizontally in the position of the original sediments, they would undoubtedly cover double the space. Now, supposing the strata here are only 10,000 feet thick—a very moderate estimate—in mashing to one half the extent, they would be thickened to 20,000 feet, which would be a clear elevation of 10,000 feet if they were not subsequently eroded. According to Renevier, a section of the Alps reveals seven anticlines and corresponding synclines, and some of them are complete overfolds (Fig. 230). We are safe in saying that Alpine strata have been mashed horizontally into one half their original extent. Supposing these were originally 30,000 feet thick (they were really much thicker), this would make a clear elevation of 30,000 feet. Of course, most of this has been cut away by erosion. In the Appalachian range, according to Claypole, the foldings are so extreme that in one place 95 miles of original extent have been mashed into 16 miles, or six into one, and yet the Appalachian strata are estimated as 40,000 feet thick. Cases of still greater doubling of strata upon themselves occur. In the Highlands of Scotland the strata by lateral thrust were broken and slidden one over another for ten miles. In the Canadian Rocky Mountains there is an overthrust of seven miles, by which the Cambrian is made to override the Cretaceous, and 50 miles of strata are mashed into 25 miles (McConnell). In the Appalachians of Georgia the *Rome fault* is an overthrust which brings the Cambrian in contact with the Carboniferous and the fault under different names may be traced northward for 275 miles; and in the Cartersville thrust-fault there is an overriding of 11 miles (Hayes). The manner in which this is done is illustrated on a previous page (Fig. 209). Evidently, then, the whole height of the mountains mentioned above is due to lateral crushing alone."

If Professor Leconte had been familiar with the folding produced in the sea trenches he could have completed the theory of mountain formation developed in this paper. As geologists have for centuries recognized the fossils found in mountains as having been deposited in the sea, it is remarkable that the suggestion seems never to have occurred to them that the folding was done in the sea before the land was lifted above the water, and by earthquake processes due to the sea itself. Leconte, however, came very near this view, as the following will show (p. 267 et seq.):

"*Mountains are made out of lines of thick sediments.*—But the question occurs, What determines *the place* of a mountain-range? The answer is, A mountain-range while in preparation—before it became a range—was a line of very thick sediments. This is a very important point in the theory of mountain origin, and therefore must be proved. The strata of all mountains, where it is possible to measure them, are found to be of enormous thickness. The strata involved in the folded structure of the Appalachian, according to Hall, are 40,000 feet thick, the strata exposed in the structure of the Wahsatch, according to King, are more than 50,000 feet thick; the Cretaceous strata of the Coast Range, near the Bay of San Francisco, according to Whitney, are 20,000 feet thick; and if we add to this 10,000 feet for the Eocene and Miocene strata, the whole thickness is probably not less than 30,000 feet, while the Cretaceous alone in Northern California, according to Diller, is 30,000 feet. The Alpine geologists estimate the thickness of the strata involved in the intricate structure of the Alps as 50,000 feet. The strata of Uintah, according to Powell, are 32,000 feet thick.

"Now, it must not be imagined that these numbers merely represent the *general* thickness of the stratified crust; only that in these places the strata are turned up and their edges exposed by erosion, and thus their thickness revealed. On the contrary, it may be shown that the same strata are much thinner elsewhere. The same strata which along the Appalachian range are 40,000 feet thick, when traced westward thin out to 4,000 feet at the Mississippi River. The same strata which along the line of the Wahsatch are 30,000 feet thick, when traced eastward thin out to 2,000 feet in the region of the plains. It is evident, therefore, that mountain-ranges are lines of *exceptionally* thick strata.

"*Mountain-ranges were once Marginal Sea-Bottoms.*—Where, then, do sediments now accumulate in greatest thickness? Evidently on marginal sea-bottoms, off the coasts of continents. The greater part of the washings of continents are deposited within 30 miles of shore, and the whole usually within 100 miles. From this line of thickest and coarsest deposit the sediments grow thinner and finer as we go seaward. But evidently such enormous thicknesses as 40,000 feet cannot accumulate in the same place *without pari passu subsidence* such as we know takes place now whenever exceptionally abundant sedimentation is going on (p. 145). Therefore, *mountain-ranges before they were yet born*—while still in preparation as embryos in the womb of the ocean—*were lines of thick off-shore deposits gradually subsiding,* and thus ever renewing the conditions of continuous deposits.

"As this is a very important point, it is necessary to stop here awhile in order to show that such was actually the fact in the case of all the principal ranges of the American Continent—*i. e.,* that for a long time before they were actually formed, the places which they now occupy were marginal sea-bottoms receiving abundant sediments from an adjacent continent. We shall be compelled to anticipate some things that belong to Part III, but we hope to make statements so general that there will be no difficulty in understanding them.

"1. *Appalachian.*—The history of this range is briefly as follows: At the beginning of the Palæozoic era there was a great V-shaped land-mass, occupying the region now covered by Labrador and Canada, then turning northwestward from Lake Superior and extending perhaps to polar regions about the mouth of the Mackenzie River. This is shown on map, Fig. 269, on page 303. There is another great land-mass occupying the present place of the eastern slope of the Blue Ridge and extending eastward probably far beyond the present limits of the continent—as shown in the same figure by dotted line in the Atlantic Ocean. The western coast-line of this land-mass was the present place of the Blue Ridge. Westward of this line extended a great ocean—'the interior Palæozoic Sea.' The Appalachian range west of the Blue Ridge was then the *marginal bottom of that sea.* During the whole of the Cambrian, Silurian, and Devonian, this shoreline remained nearly in the same place, although there was probably a slow transference westward. Meanwhile, throughout this immense period of time, the washings from the land-mass eastward accumulated along the shore-line, until 30,000 feet of thickness was attained. At the end of the Devonian some considerable changes of physical geography of this region took place, which we will explain when we come to treat of the history of this period. Suffice it to say now that during the Carboniferous the region of the Appalachian was sometimes above the sea as a coal-swamp, and sometimes below, but all the time receiving sediment until 9,000 or 10,000 feet more of thickness was added, and the aggregate thickness became

40,000 feet. Of course, it is impossible that such thickness could accumulate on the same spot without *pari passu* subsidence of the sea-floor. In fact, we have abundant evidences of comparatively shallow water at every step of the process—evidence sometimes in the character of the fossils, sometimes in the form of shore-marks of all kinds, sometimes in the form of seams of coal, showing even swamp-land conditions. Again, of course, the sediments were thickest and coarsest near the shore-line, and thinned out and became finer towards the open sea, *i. e.*, westward. Finally, after 40,000 feet of sediments had accumulated along this line the earth-crust in this region gave way to lateral pressure, and the sediments were mashed together and folded and swollen up into the Appalachian range. Subsequent erosion has sculptured it into the forms of scenic beauty which we find there to-day.

"2. *Sierra.*—This was apparently the *first-born* of the Cordilleran family. Its history is as follows: During the whole Palæozoic and earlier part of the Mesozoic, there was in the Basin region a land-mass, whose form and dimensions we yet imperfectly know, but whose Pacific shore-line was *east of the Sierra.* The Sierra region was therefore at that time the marginal bottom of the Pacific Ocean. Probably the position of this shore line changed considerably at the end of the Palæozoic. The extent of this change we will discuss hereafter. Suffice it to say now that, during the whole of this time, the Sierra region received sediments from this land-mass until an enormous thickness (how much we do not know, because the foldings are too complex to allow of estimate) was accumulated. At last at the end of the Jurassic, the sea floor gave way to the increasing lateral pressure along the line of thickest sediments, and these latter were crushed together with complex foldings and swollen up into the Sierra. An almost inconceivable subsequent erosion has sculptured it into the forms of beauty and grandeur which characterize its magnificent scenery.

"3. *Coast Range.*—The birth of the Sierra transferred the Pacific shoreline westward, and the waves now washed against the western foot of that range, or possibly even father westward in the region of the Sacramento and San Joaquin plains. At this time, therefore, the region of the Coast Range was the marginal bottom of the Pacific Ocean. During the whole Cretaceous, Eocene, and Miocene, this region received abundant sediments from the now greatly enlarged continental mass to the eastward; until finally, at the end of the Miocene, when 30,000 feet of sediments had accumulated along this line, the sea-floor yielded to the lateral pressure, and the Coast Range was born; and the coast-line transferred to near its present position.

"4. *Wahsatch.*—The physical geography of the region to the east of the Wahsatch (Plateau region) during Jura-Trias time is little known. But during the Cretaceous the region of the Wahsatch was the western marginal bottom of the great interior Cretaceous Sea (see map, Fig. 760, p. 486), receiving abundant sediments from the great land-mass of the Basin and Sierra region. This greatly increased the enormous thickness of sediments already accumulated along this line in earlier times. At the end of the Cretaceous the sediments yielded, and the Wahsatch was born. It is necessary, however, to say that both the Sierra and Wahsatch underwent very great changes of form produced by a different process and at a much earlier period. We shall speak of this later.

"5. *Alps.*—Mr. Judd has recently shown that the region of the Alps, during the whole Mesozoic and Early Tertiary, was a marginal sea bottom, receiving sediments until a thickness was attained not less than that of the Appalachian strata. At the end of the Eocene these enormously thick sediments were crushed together with complicated foldings and swollen upward to form these mountains and afterward sculptured to their present forms.

"The same may be said of the Himalayas and nearly all other mountains. We may, therefore, confidently generalize, and say that the place now occupied by mountain-ranges have been previous to their formation, places of great sedimentation, and therefore usually marginal *ocean bottoms.* In some cases, however, the deposits in interior seas or mediterraneans have yielded in a similar way, giving rise to more irregular ranges or groups of mountains." . . .

"*Why thick Sediments should be Lines of Yielding.*—Admitting, then, that mountains are formed by the squeezing together of lines of very thick sediments, the question still occurs, *Why does the yielding take place along these lines in preference to any others?* This is a capital point in the theory of mountain formation. The answer is as follows: We have already seen (p. 231) that accumulation of sediments causes the isogeotherm to rise and the interior heat of the earth to invade the lower portion of the sediments with their included waters. Now this invasion of heat in its turn causes hydrothermal softening or even fusion, not only of the sediments, but also of the sea-floor on which they rest. Thus a line of thick sediments becomes a line of softening and therefore a line of weakness, and a line of yielding to the lateral pressure, and therefore a line of mashing together and folding and upswelling—in other words a mountain-range. As soon as the yielding commences we have an additional source of heat in the crushing itself. In addition to this, upheaval by lateral crush by the tendency to arch the strata would produce relief of gravitative pressure, and therefore fusion (p. 103). It follows from this that there is or was beneath every mountain a line of fused or semi-fused matter. This we will call the *sub-mountain liquid.* This by cooling and solidification becomes a *metamorphic or granitic core,* which by erosion forms the metamorphic or granitic axis and crest of many great mountains" . . . (pp. 271–2).

"*Cause of Lateral Pressure.*—We have thus proved that the immediate cause of the origin and the growth of mountains is lateral pressure acting on thick sediments, crushing them together and swelling them up along the line of great thickness. But still the question remains, What is the *ultimate* cause, *i. e.,* the *cause of the lateral pressure?* This, as we have already said, lies still in the domain of doubt and discussion, but the view which seems most probable may be briefly stated as follows:

"In the secular cooling of the earth there would be not only unequal radial contraction, giving rise, as shown on page 175, to continents and ocean-basins, but also to unequal contraction of the *exterior* as compared with the *interior.* At first, and for a long time, the exterior would cool fastest; but there would inevitably, sooner or later, come a time when the exterior, receiving heat from abroad (sun and space), as well as from within, would assume an almost constant temperature, while the interior would still continue to cool, and contract. Thus, therefore, after a while the interior nucleus would contract faster than the exterior shell. It would do so, partly because it would cool faster, and partly because the coefficient of contraction of a hot body is greater than that of a cooler body. Now, as soon as this condition was reached, the exterior shell, following down the shrinking nucleus, would be thrust upon itself by a lateral or horizontal pressure which would be simply irresistible. If the earth's crust were a hundred times more rigid than it is (thirty times as rigid as steel, 500 to 1,000 times as rigid as granite—Woodward, *Science,* Vol. XIV, p. 167, 1889), it must yield. Mountain-ranges are the lines along which the yielding takes place, and this yielding takes place along the lines of thick sediments because these are lines of weakness.

"There are several serious objections which may be brought against this view: 1. Calculations seem to show that the amount of crumpling and folding actually found in the mountains is many times greater than could be produced by the contraction of the earth by *cooling*. But it may be answered (1) that the calculations take no account of the greater coefficient of contraction at high temperatures, and therefore at great depths, (2) and that there may be *other causes* of contraction besides cooling. For example, loss of constituent gases and vapors from the interior of the earth, through volcanic vents and fissures, has been suggested by O. Fisher (p. 102).

"2. Again, it has been shown by Dutton that it is impossible that the effects of differential contraction should be concentrated along certain lines, so as to give rise to mountain-ranges without a shearing of the crust upon the interior portions, which is inadmissible if the earth be solid. Instead, therefore, of conspicuous mountain-ranges, the effects of differential contraction would be distributed all over the surface, and be wholly imperceptible. But in answer to this it may be said that there is no difficulty in the way of shearing, and therefore of such concentration of effects along certain lines, if *there be a sub-crust liquid* or semi-liquid layer, either universal or else underlying large areas of surface.

"Still other objections have been raised, but these are so recent that they have not yet been sufficiently sifted by discussion to deserve mention here.[1] The origin of mountains by lateral pressure is a fact beyond dispute. This is the most important fact for the geologist. How the lateral pressure is produced is a pure physical question which must be left to the physicists to settle among themselves" (pp. 274–5).

Leconte treats also of Monoclinal mountains, as found in the Great Basin, which he explains by normal faulting, or vertical movement of crust blocks, and finally adds:

[1] For a completer discussion of this subject, see "Theories of Mountain Origin," *Jour. Geol.,* Vol. I., p. 542, 1893.

"Thus, then, there are two types of mountains strongly contrasted, mountains of the one type are formed by lateral *pressure and crushing,* of the other type by lateral *tension and stretching.* The one gives rise mainly to reverse faults, the other always to normal faults. Mountains of the one type are formed by upswelling of thick sediments, those of the other type by irregular readjustment of crust-blocks. Mountains of the one type are *born of the sea,* those of the other type are born *on the land.* We find examples of the one type in nearly all the greatest mountains everywhere, but especially in the Appalachian, the Alps and the Coast Range. The best examples, perhaps the only examples, of the other type are the Basin ranges. Some mountains, as the Sierra, the Wahsatch, and certainly *some* of the Basin ranges, belong to both types. In their origin, they have formed in the first way, but afterward have been modified by the second way. Thus the first is the fundamental method, and the second only a modifying process" (p. 277).

These views of Leconte call for no special comment, beyond the remark that normal faulting itself is wholly unexplained. If secular cooling were the cause, such faults ought to occur east of the Rocky Mountains as well as west of them. The important difference is that the Pacific Ocean was on the west pushing up the land, and a continental basin on the east, either dry or covered by shallow water and therefore doing little or no pushing at all. In any case the great plateaus of the west were certainly uplifted by the Pacific, through the expulsion of lava under the land. In the Andes of South America the plateaus are higher indeed, but also narrower than those in North America, because in our continent the relief resulting from the leakage of the ocean took a broader and less elevated form. It is impossible for any one to doubt the identity of the forces which raised the Andes and their plateaus, the Himalayas and their plateaus, and the Rocky Mountains and the mountains and plateaus of the Great Basin. The principle of continuity shows clearly that the cause was everywhere one and the same. Several American geologists have suggested vertical uplifts in the Great Basin, from the way in which the crust blocks are displaced; but heretofore no known cause for such movements could be assigned, because it was held that secular cooling is the chief if not the only cause operating in the development of the globe.

§ 43. *Views of Rev. O. Fisher.*—The Rev. O. Fisher was the first to show by long and patient research the total inadequacy of secular cooling to account for the observed height of mountains.

He showed that the mountains are hundreds of times higher than the cooling of the earth will explain. On this point his labors mark a distinct advance in geological science; for next in importance to establishing true theories is the overthrow of erroneous ones, which clears the ground for a fresh start. But notwithstanding the unanswerable character of Fisher's argument, the old theories have been retained by geologists as the best they could devise. Fisher's criticisms of geological theories are carefully thought out, and worthy of attention. He has always denied the entire solidity of the earth, holding that the movements noticed in mountains proved the existence of a mobile substratum beneath a crust some twenty miles thick. Here again he was certainly right, and it is difficult to see how such an obvious proposition could be denied.

We need not dwell on Fisher's views of mountain formation, because they imply convection currents within the earth, and these latter are certainly inadmissible, except just beneath the crust in earthquake movements, as developed in the theory set forth in this paper.

§ 44. *Views of Major C. E. Dutton.*—Like the Rev. O. Fisher, Major Dutton was one of the earliest authorities to question the adequacy of secular cooling to account for the wrinklings noticed in the earth's crust. Using the results of Fourier's solution for the variation of temperature, as developed in the work of Lord Kelvin, Dutton found that

"the greatest possible contraction due to secular cooling is insufficient in amount to account for the phenomena attributed to it by the contraction hypothesis. By far the larger portion of this contraction must have taken place before the commencement of the Palæozoic age. By far the larger portion of the residue must have occurred before the beginning of the Tertiary, and yet the whole of this contraction would not be sufficient to account for the disturbances which have occurred since the close of the Cretaceous."

Major Dutton concludes that "the determination of plications to particular localities presents difficulties in the way of the contractional hypothesis which have been underrated." He held that the localization of the plications could result only from a large amount of horizontal slipping of the crust over the nucleus, and the friction involved in this movement even over a liquid nucleus would be so great as to render the assumption a physical absurdity.

If wrinkling resulted from uniform cooling and consequently uniform shrinkage, the effect would be analogous to that of a withered apple, with small wrinkles all over it, instead of a surface presenting in one region a continuous system of folds extending from Cape Horn to Alaska, and in another, a zone a thousand miles wide, from the Appalachian to the Rocky Mountains, with scarcely any evidence of disturbance whatever.

In these considerations Major Dutton has forcibly expressed the difficulty of supposing that a mountain range is formed by the cooling of the earth contracting equally along all its radii. Such a supposed mode of formation of our ranges, folded and crumpled as they are, is clearly impossible; and Major Dutton shares with the Rev. O. Fisher the credit of having been the first to recognize the total inadequacy of the contraction theory.

It is remarkable that after this antiquated theory had been thus clearly disproved, it should have continued in use. No one seems to have been able to frame a theory based on any cause except secular cooling, till the present writer developed the theory based on the leakage of the oceans and the formation of mountains by the expulsion of lava under the land, which perfectly explains all the phenomena.

§ 45. *Views of Geikie.*—In the article "Geology," *Encyclopedia Britannica,* p. 375, we find the following statement of the contraction theory:

"There still remains the problem to account for the original wrinkling of the surface of the globe, whereby the present great ridges and hollows were produced.

"It is now generally agreed that these inequalities have been produced by unequal contraction of the earth's mass, the interior contracting more than the outer crust, which must therefore have accommodated itself to this diminution of diameter by undergoing corrugation. But there seems to have been some original distribution of materials in the globe that initiated the depressions on the areas which they have retained. It has been already pointed out (ante, p. 223) that the matter underlying the oceans is more dense than that beneath the continents, and that, partly at least, to this cause must the present position of the oceans be attributed. The early and persistent subsidences of these areas, with the consequent increase of density, seems to have determined the main contours of the earth's surface. . . .

"The effects of this lateral pressure may show themselves either in broad dome-like elevations, or in narrower and loftier ridges of mountains.

The structure of the crust is so complex, and the resistance offered by it to the pressure is consequently so varied, that abundant cause is furnished for almost any diversity in the forms and distribution of the wrinkles into which it is thrown. It is evident, however, that the folds have tended to follow a linear direction. In North America, from early geological times, they have kept on the whole on the lines of meridians. In the Old World, on the contrary, they have chosen diverse trends, but the last great crumplings —those of the Alps, Caucasus, and the great mountain ranges of central Asia—have risen along parallels of latitude.

"Mountain chains must therefore be regarded as evidence of the shrinkage of the earth's mass. They may be the result of one movement, or of a long succession of such movements. Formed on lines of weakness in the crust, they have again and again given relief from the strain of compression by undergoing fresh crumpling and upheaval."

Geikie's views may be considered the accepted views of geologists generally, and it will be seen that they rest on the theory of contraction due to secular cooling.

On the constitution of the globe Geikie quotes ("Geology," p. 73) from the paper of Arrhenius, "Zur Physik des Vulcanismus" (1900), the following theory of the illustrious Swedish physicist:

"If the rocks at the earth's surface have a density half that of the globe as a whole, and if the density continues to hold good for the magma that arises from the melting of these rocks, we must conceive the existence of a much denser substance in the earth's interior. On various grounds, such as the preponderance of iron in nature, both in meteorites and in the sun, and the phenomena of terrestrial magnetism, it may be inferred that this substance is metallic iron. In consequence of its greater density this iron will naturally be deeper than the rock magma, and on account of the high temperature must exist in a gaseous condition. Somewhere about a half of the planet therefore should consequently consist of iron, and of other metals mingled with it in smaller proportions. The semi-diameter of this gaseous iron-sphere will thus include about 80 per cent. of the earth's semi-diameter. Then will come about 15 per cent. of the gaseous rock magma, next to it the liquid rock-magma for a thickness of about 4 per cent. of the terrestrial semi-diameter, and lastly the solid crust, for which not more than 1 per cent. may be claimed" (pp. 404–5).

Referring to the light thrown on the constitution of the interior by the observation of waves propagated by earthquakes, Geikie also adopts the theory of Arrhenius, which is as follows:

"The density of much the largest part (reckoned linearly) of this interior, amounting, as above stated, to about 80 per cent. of the radius, must be nearly three times higher than that of quartz. Since now the mean velocity of transmission of earthquake waves in the interior of the earth has been ascertained to amount to 11.3 kilometers per second, the compressibility of that region must be 31 times less than that of quartz, that is, eight times less than that of solid steel, according to Voigt. This is a figure of precisely that order of magnitude which was to be expected. We may well believe that at depths of more than 1,000 kilometers the compressibility of gaseous iron sinks down to some ten times less than that of steel.

"The interior of the earth, therefore, with the exception of a solid crust about 40 kilometers thick, consists of a molten magma 100 or 200 kilometers in depth which shades continuously inward into a gaseous center. The liquids and gases in the interior possess a viscosity and incompressibility such as permit them to be regarded as solid bodies. From these, however, they are distinguished in the first place by the fact that differentiations are possible to a considerable degree, the effects of which may long endure. In the second place, long continued pressures, when acting on a large enough scale, may produce great deformations. Further, the liquids must possess the property of great expansion on a diminution of the high pressure, thereby readily becoming fluid. The process must thus differ but little from a normal melting with increase of volume, and especially of fluidity, as well as with absorption of heat. And yet the condition of aggregation is not thereby altered."

Geikie remarks that the theory of Arrhenius accords well with geological requirements:

"With reference to the crust of the earth, it meets the constantly repeated objections of the geologists to whom the existence of a comparatively thin crust has always seemed an essential condition for the production of that crumpled and fractured structure which the rocks of the land so universally present. If the solid crust of the earth is allowed to be about 25 miles thick, we must conceive that in the lower four fifths of its mass the rocks are in a condition of latent plasticity. They lie much beyond the crushing strength which they exhibit at the surafec. They are not crushed into powder as they would be under a similar strain above ground, but they are ready to yield to the deformations that may arise consequent upon adjustments of the gigantic pressure to which they are subjected. Hence the solid crust down as far as its structure has been disclosed abounds in proofs that it has undergone colossal plication and fracture, and that higher portions of it many square miles in extent have been thrust bodily over each other for many miles."

The last view here expressed by Geikie as to how the crust becomes thrust over itself for many miles is not, we think, well founded, because it is shown in this paper that all this folding and overlapping of the crust arises in the trenches dug out in the sea bottom by earthquakes. This crumpling and overthrusting of the crust certainly would not arise except for earthquakes produced by the leakage of the oceans, to which mountain formation is due. Of course the plasticity of this layer beneath the crust contributes to the final result, but the leakage of the oceans, with the resulting earthquakes, supplies the deforming force.

§ 46. *Views of Professor Suess.*—In the "Face of the Earth" (Vol. I, p. 107) we find the following brief exposition of Professor Suess' views:

"*The dislocations visible in the rocky crust of the earth are the result of movements which are produced by a decrease in the volume of our planet.* The tensions resulting from this process show a tendency to resolve themselves into *tangential* and *radial* components, and thus into horizontal (*i. e.*, thrusting and folding), and into vertical (*i. e.*, sinking) movements. Dislocations may therefore be divided into two main groups, of which one is produced by the more or less horizontal, the other by the more or less vertical relative displacement of larger or smaller portions of the earth's crust.

"There are large areas in which the first, and others in which the second group predominates, and there are also regions in which both groups appear together, and in which an intimate connection may be recognized between them, the resolution of the movements in space having in these cases been less complete. This essential difference in the movements of the lithosphere may be clearly perceived from a comparative study of the structure of the Old World; nor has it escaped the notice of American geologists.

"'The geological provinces of the Great Basin,' remarks Clarence King, has suffered two different types of dynamic action: one in which the chief factor was evidently tangential compression, which resulted in contraction and plication, presumably in post-Jurassic time; the other of strictly vertical action, presumably within the Tertiary, in which there are few evidences or traces of tangential compression.'

"Our colleagues on the other side of the ocean have even gone a great deal further. After comparison of the folded Appalachian mountains with the depressed Basin Ranges, Gilbert had in 1875 already suggested the possibility that in the Appalachians the causes of movement were superficial, in the Basin Ranges deep-seated. We shall have an opportunity, when discussing the relation of the Alps to their northern foreland, of determining to what extent this supposition finds confirmation in Europe. We may however state at once that as a rule it is only the dislocations of the second group which are accompanied by volcanic eruptions."

§ 47. *Views of Arrhenius.*—It is well known that this distinguished Swedish physicist holds that the earth's interior is essentially gaseous (cf. § 45, above), but under the great pressure operating in the globe made to behave very nearly as a solid.[1] In his

[1] See Postscript, page 274.

paper "Zur Physik des Vulcanismus," published in 1900, Arrhenius points out that in fluids at high temperature, where no increase in volume takes place, the internal friction of the molecules rises with the temperature, so that the viscosity increases and the fluidity diminishes; that a similar effect is observable in both gases and liquids; that although gases have the highest and solids the lowest compressibility, nevertheless when a gas near its critical temperature passes into a liquid, through a trifling physical change, there is practically no change in the compressibility. The higher the pressure the smaller is the compressibility, and a gas above the critical temperature may be made to acquire the properties of a solid by pressure alone. Such a mass has great density, small compressibility, and large viscosity, so that it has the properties of a solid, though really an imprisoned gas.

At a depth of 40 kilometers Arrhenius says the temperature is about 1200° C., and the pressure about 10,840 atmospheres; and as these conditions would render nearly all ordinary minerals fluid, he concludes that below that depth the matter is molten, in the form of a magma—that is, a viscous and nearly incompressible liquid made to act nearly as a solid by pressure.

At greater depths the temperature is above the critical temperature of every known substance, as the pressure rapidly increases and the liquid magma becomes a gaseous magma with larger and larger viscosity, and smaller and smaller compressibility—in other words, an elastic solid with rigidity increasing with the depth.

VI. Abandonment of the Old Theories of the Physics of the Earth.

§ 48. *The Total Inadequacy of the Old Theories to Account for the Fault Movements near the Sea, which Raise Vertical Blocks and Walls of Granite*[1] *Thousands of Feet above the Water.*—The vast

[1] Andesite is the name used to designate the kind of granitic rock found in the Andes. Charles Darwin showed that all granitic rocks are closely related. In his "Text-book of Geology," edition of 1903, book II, Part II, § 7, pp. 230–260, Sir Archibald Geikie gives tables of the chemical compositions of all these rocks, which show very clearly their close relationship. When we use the term *granite* therefore we mean *granitic rock* in the wide sense.

vertical walls and blocks of granite so often lifted thousands of feet above the sea, with deep water all around their bases, frequently encountered in different parts of the world, cannot be explained except by the present theory. Thus along the west coast of Chili and Patagonia, from Cape Horn to Valparaiso, in the Straits of Magellan, as well as in the ranges of the Andes further from the coast, in the Sierras of California, and elsewhere these vertical uplifts are common. It is obvious that they cannot possibly be explained by the old theories depending on the shrinkage of the globe. But if lava is expelled from beneath the sea, owing to the secular leakage of the ocean bottom, and the crust is fractured and rent into blocks by the earthquake forces, some of these blocks would naturally be pushed upward, leaving vertical walls of granite thousands of feet high. Occasionally the blocks would be forced apart, leaving the sea pass between, as so often seen in Chili, Patagonia and Tierra Del Fuego. The Straits of Magellan no doubt arose in this way. As already remarked in § 27, Darwin describes similar breaks in the Andes further north, through which the sea once flowed, but they are now raised above the water. No doubt the time will come when Tierra Del Fuego will be joined solid to Patagonia, by uplifts which will cause the sea to withdraw from the Straits of Magellan and it will become dry land, like those ancient passages further north mentioned by Darwin.

There are many other parts of the world where similar phenomena may be seen. The origin of the fiords in Norway has long been a matter of debate. It seems to be conceded that these inlets are made by mountains running into the sea, and more or less modified above water by ice and glaciers. They are supposed to be quite old, and certainly date back of the glacial epochs.

It may no doubt be safely assumed that these Norwegian mountains originated, like other mountains, by the uplift of faults, owing to the expulsion of lava from beneath the sea.[1] Hence the precipitious walls along the sea coast, with deep water between. The blocks

[1] Having read the earlier papers of this series with great interest, Professor Schiaparelli has kindly called my attention to the trough in the sea along the Norwegian coast. This confirmation of the theory by the illustrious astronomer of Milan is exceedingly interesting.

of the earth's crust were lifted vertically by the pushing of lava beneath them. It is in this way that all such walls of granite and other towering rock are to be explained, and the fact that the sea still encroaches on them shows how the movements came about. Probably there has been little vertical movement for a long time along the coast of Norway, and subsidence as well as elevation may have taken place, both here and elsewhere. Subsidence is common along most sea coasts, but it does not prevail in the long run, as is proved by Professor Suess's work, showing a universal lowering of the strand line throughout the world.

§ 49. *The Theory of Arches and Domes Inapplicable to the Crust of the Earth, because the Globe is not Shrinking but actually Expanding.*—In Chamberlin and Salisbury's "Geology," Vol. I, p. 583, we find the statement that

"The principle of the dome is brought into play whenever an interior shell shrinks away, or tends to shrink away, from an outer one which does not shrink. In this case there is a free outer surface and a more or less unsupported under surface towards which motion is possible. The dome may, therefore, yield by crushing or by contortion."

Owing to the important part the domed form of the crust has played in theories of deformation, these authors give quantitive results calculated by Hoskins, showing that such a dome of continental dimensions, if unsupported from below, *would sustain only 1/525th of its own weight.*

In his consideration of the "Mathematical Theories of the Earth" (*Proc. Am. Assoc. for Adv. Sci.,* 1889, p. 49), Professor R. S. Woodward reached the analogous conclusion that "If the crust of the earth were self-supporting, its crushing strength would have to be about thirty times that of the best cast steel, or five hundred to one thousand times that of granite."

In view of these results it is remarkable that any one should have viewed the earth's crust as a wholly or partially self-supporting dome; for it could not be supported even over a very small area. And moreover secular cooling is wholly inadequate to cause a separation of the interior layers from the crust. All that has been published on this point, therefore, is inapplicable to the earth, because it rests on a false hypothesis. The supposed conditions have no reality.

The earth is not shrinking and the crust does not tend to separate itself from the underlayers, except where the lava has been expelled from beneath it by earthquakes. The collapse of the crust when thus undermined, however, shows that it will not support its own weight even for a short distance. Over such small areas the crust may be taken as part of a plane, or sometimes as concave, where subsidence is already at work, and hence the theory of the arch or dome is scarcely applicable; yet the observed collapse and sinking, even where the area is no larger than in ocean troughs, confirms the above conclusions regarding the total inability of the crust to support itself.

Could therefore anything be more absurd than to discuss the stresses in the crust due to the progress of secular cooling? Stresses arise only where mountain making is in progress, and therefore chiefly near the oceans, but never appear far inland; and are wholly due to the pressure arising from steam-saturated rock and the expulsion of lava from beneath the oceans, or to movements traceable to surface water slowly sinking into the earth. The theory of arches and domes therefore confirms the present theory, but this result is indirect; and such lines of thought did not enable geologists and physicists to reach correct conceptions regarding the physics of the earth's crust.

§ 50. *On the Doctrine that Earthquake Movements depend on Slight Inequalities of Loading, and on the Abandoned Theory that the Earth is a Failing Structure.*—As the crust of the earth is made up of solid rock and soil arising from the disintegration of rock of various kinds, and as this material is elastic and yields under pressure, it naturally occurred to physicists that inequalities of surface loading deposited on adjacent areas would impose upon the underlying crust unequal stresses, and perhaps give rise to relative movements. Thus many physicists, in default of a better theory, have supposed that surface loads, depending on erosion and sedimentation, tides and varying barometric pressure, would be adequate to produce stresses that would cause readjustment of the surface strata and perhaps movements of faults in earthquakes.

It is undeniable that these varying loads do produce some small effects, and very slight changes of level may often arise in this way. We owe the establishment of these effects of loading chiefly to the researches of Professor Sir G. H. Darwin, whose labors have so greatly advanced our knowledge of the physics of the earth. They have an extremely high importance in the theory of bodies approximating elastic solids. The undisturbed crust of the globe fulfills these conditions quite perfectly.

But to suppose that any of these small surface effects could give rise to world-shaking earthquakes which would shake down cities, raise sea coasts, and uplift mountains and islands in the sea, is too severe a test of credulity to be entertained. The class *of minute movements,* due to surface yielding under varying loads depending on sediments, tides and meteorological causes, and the class of *great movements,* due to the expulsion of lava from under the bed of the sea, are quite distinct. One class of these phenomena is microseismic, the other magaseismic. Previous investigators have generally confounded the two classes of phenomena, and hence they have been unable to recognize the true cause of earthquakes and mountain formation. For that reason it was necessary to restrict our investigation to the great disturbances, in the first search for the cause of the great movements of the earth's crust.

We repeat that both classes of phenomena are important in a complete theory of the physics of the earth; but the small yieldings of microscopic dimensions must be kept distinct from the great movements which have shaped the surface of the globe. Many of the small effects depend on the greater movements of the earth, while few of the great movements are influenced by surface forces—indeed none at all, except where accumulation of subterranean stresses has already rendered the conditions highly unstable. In this latter case small surface forces may occasionally accelerate the outbreak of an earthquake, just as a spark discharges a loaded gun, or a shock explodes a charge of dynamite.

On a par with the theory that slight inequalities of surface loading produce earthquakes is another equally untenable view that the earth is a failing structure. Such a doctrine might have been entertained a quarter of a century ago, when the theory of secular cooling was generally accepted, but to-day such a view is antiquated and utterly indefensible. *Owing to the demonstrated de-*

pendence of mountain making upon the sea the earth emphatically is not a failing structure. So far from failing by collapse, our planet seems to be expanding from 10 to 100 faster than it contracts from loss of heat. Thus have arisen all the highest mountains and plateaus of the globe. These great uplifts invariably face the deepest oceans, from which the expulsion of lava has mainly proceeded. Such antiquated doctrines as that the earth is a failing structure are now absolutely without excuse, and practically abandoned, and the sooner they disappear from scientific literature the better for sound knowledge of the physics of the earth.

§ 51. *Changes of the Force of Gravity in Regions Affected by the Movement of Lava Beneath the Crust.*—In view of the demonstrated movement of lava streams beneath the crust of the globe, it follows that such bodily displacement of matter but a short distance below the surface may modify sensibly the observed intensity of gravity. A region which is being undermined will have the intensity of gravity decreased, and a region which is being filled up will have the attraction increased. And not only will the *intensity* vary, but also the *direction* of the vertical, according to the movements which occur beneath the crust. And these effects may be large enough to become sensible to very refined observation.

It is in this way that the anomalies of gravity in the neighborhood of mountains have arisen in the process of mountain formation. And in regions where the expulsion of lava is still in progress, both the direction and intensity of gravity are subject to change by earthquakes. Thus in the region of the Aleutian Islands, the east coast of Japan, and many other places, such as the west coast of South America, the direction and intensity of gravity is certainly subject to change by seismic disturbances.

As the crust of the globe often suffers horizontal and vertical movement during the greatest earthquakes, the *altitude* and *azimuth* of places are also subject to change; and exact geodetic triangulation remains valid only for the interval between great earthquakes. Even then there may be a very slow and gradual settlement owing to plastic yielding of the crust and especially of the substratum beneath. Thus after earthquakes such as occur in Peru and Chili, Japan and Alaska, gravity and geodetic determinations need repetition, as was done in California after the great earthquake of April 18, 1906. And as the disturbance may alter the direction and intensity of local gravity, this possibility must be taken account of in the repetition of the observations. In order to be entirely rigorous the equations connecting the triangulation should include undetermined multipliers to take account of possible variations in the local attraction at each point. If with this general condition imposed, the triangulation before and after the earthquake comes out rigorously the same, within the limits of errors of observation, it may be supposed that the surface effects of the disturbance are insensible; otherwise the difference must be attributed to disturbances due to the earthquake.

With the refinement now possible in geodesy, it is not to be doubted that these effects will occasionally prove to be sensible to observation. The great earthquake in Assam-Bengal gave rise to horizontal movements of the order of 20 or 30 feet, which may affect the latitude by 0″.2 or 0″.3, and are thus within the limits of astronomical measurement. But apparent changes in latitude may result from change in the direction of gravity as well as from actual displacements of the crust, and both possibilities need to be taken into account.

§ 52. *The Necessity of Further Study of the Contours and Movements of the Sea Bottom.*—In view of the results brought out in this paper and those which have preceded it, but especially that on "The New Theory of Earthquakes and Mountain Formation as Illustrated by Processes now at Work in the Depths of the Sea," it is scarcely necessary to point out the extreme importance of further study of the contours and movements of the sea bottom. Our present maps of the ocean depths are very incomplete, although they afford a good general idea of the sea basins. But one can scarcely doubt that more exact surveys would bring to light additional mountain ranges and plateaus in regions heretofore but slightly explored; moreover certain places in the sea bottom would be found to be covered with a great variety of peaks or submerged islands which do not reach the surface.

Where the water is deep the exact survey of the bottom presents considerable difficulty. As movements arising from earthquakes are extremely small in comparison with the depth of the sea, it would perhaps be very difficult to detect resulting changes of the sea bottom, except in cases where sinking takes place, and the drop is large. In some cases of actual measurement in the laying of cables the sinking has been found to be hundreds of fathoms, which would be very easily recognized if the exact place of former soundings could be found. But as the changes of level in the sea bottom are fully as capricious as on land, we see that regions where mountain formation is in progress would present extreme complexity; and unless the place were very accurately known, one could not be sure that two soundings were over the same spot. This difficulty would be less near known islands than in the open sea, but it would be considerable in all places where the ship is at the mercy of the winds and currents.

Under the circumstances it is clear that great natural difficulty would arise in the exact Hydrographic survey of the deep sea, and an economic difficulty would be added, on the ground that such surveys are not required in practical navigation. Yet the laying and repair of cables would necessitate fairly accurate knowledge of the depths, and we may hope, in spite of the growth of the wireless telegraph, that our ocean surveys are still in the infancy of what they will be in another half century.

Where trenches are being dug out by earthquakes there will be the double incentive to ascertain the stage of the process and the rapidity and location of the changes. These considerations may contribute to our knowledge of particular regions; and, after all, the changes in the larger regions of the ocean bottom are small.

When the regions in which trenches are forming are once clearly recognized, attention will naturally be centered upon them, to the neglect of less disturbed areas. The most interesting regions, from a seismological point of view, are those in which islands are being uplifted and the sea bottom sinking, as near the Aleutian, Kurile and Japanese islands, the Antandes, and along the west coast of South America. But it may also be hoped that the changes in depth near individual islands, such as Guam and Martinique, will not be overlooked. Here the subsidence of the bottom often takes the form of a hole rather than of a trench. Yet in time the movements may give rise to neighboring islands. All of these considerations show the value of accurate knowledge of the sea bottom at this epoch.

§ 53. *Greatness of the Forces which Uplift and fold the Earth's Crust.*—The tremendous power of earthquake and volcanic forces has been proverbial from the earliest ages of history, and finds expression also in the universal terror thus excited among all living beings. This extreme terror is only too well justified by the vast extent of the ruin too often wrought in different parts of the world. But probably only those who have witnessed a great earthquake can adequately appreciate the awful character of the commotion, and the gigantic forces which must underly it. This is shown also by the many published attempts to belittle the significance of earthquake disasters.

Some writers of eminent mathematical learning, but apparently lacking in grasp of the larger physical phenomena, have ascribed earthquakes to inequalities of loading, changes of barometric pressure, etc., and have with strange and almost marvelous credulity believed that the settlements of the earth thus arising would shake down cities and devastate whole countries. How these learned authorities imagined that small subsidences under the steady action of these infinitesimal forces could bring about such long continued shaking and proportionately great havoc is difficult to understand. If the forces are so small, and act so slowly, is it conceivable that the yielding could be anything else than gradual and insensible? Such minute settlements evidently would be like those now experienced in dry inland regions free from real earthquakes.

The titanic nature of the forces which have uplifted islands, mountains, plateaus and continents, can scarcely be realized; yet even the ancients grasped it to some extent when they described the whole region between Naples and Sicily as underlaid by a giant, whose movements disturbed the intervening sea bottom. In his account of the Chilean earthquake of 1835, Charles Darwin showed that the entire region from the island of San Fernandez to the Andes, about 450 miles across, had been moved together by underlying forces. "There was undoubtedly a connection between the volcanic forces acting under this island, and under the continent, as was shown during the earthquake of 1835," says the great naturalist.

As such views have been carefully set forth by the greatest of original investigators, from Aristotle to Darwin, it is remarkable to witness the puny efforts which have been made to belittle these forces. A gentleman holding a university position, in a public address at Boston, recently likened the shock of an earthquake to the jar experienced by an insect attached to a reed which was bent till it snapped. According to this authority the earthquakes are due to the snapping of the rock of the earth's crust in the bending produced by secular cooling. Is it necessary to point out the misleading character of the comparison made, and this lecturer's utter inability to grasp the phenomena of nature?

An equally common fallacy is to ascribe these tremendous disturbances to inequalities of surface loading, due to geological and meterological causes. Such views seem the more surprising, because formerly they have proceeded from physicists of eminent learning. But at least partial excuse may be found in the universal acceptance of the theory of secular cooling heretofore, and in the proved rigidity of the globe, which naturally led to the supposition that the crust was adjusting itself to the shrinking sphere.

Before the development of the theory of ocean leakage no adequate theory presented itself to investigators, who had unfortunately not discriminated between the great and small earthquakes. With a false premise and such an indiscriminate mixture of phenomena, real progress was difficult, if not impossible.

§ 54. *Darwin's Remarks on the Forces which Uplift Continents.* —In the extract quoted from Professor Suess, § 39, allusion has already been made to Charles Darwin's attempt to explain the origin of mountains by the direct observation of nature. His paper "On the Connection of Certain Volcanic Phenomena in South America and the Formation of Mountain Chains and Volcanoes as the Effect of the Same Power by which Continents are Elevated" (*Transactions of the Geological Society,* Vol. V, 1838, pp. 601–631) led Darwin to the conclusion:

"That the form of the fluid surface of the nucleus of the earth is subject to some change, the cause of which is entirely unknown and the effect of which is slow, intermittent, but irresistible."

Again, in the "Voyage of the Naturalist," Chapter XIV, he adds:

"The forces which slowly and by little starts uplift continents, and those which at successive periods pour forth volcanic matter from open orifices, are identical."

It is unnecessary to dwell on the irresistible power which the great naturalist correctly abscribed to volcanic and earthquake forces. It is of more interest to notice that he declared them to be identical with those which uplift continents. The same result is reached in the present paper, about three quarters of a century later, and the proof of the proposition now seems overwhelming.

If Darwin had known the cause of seismic sea waves, and had seen how trenches are dug out in the sea bottom by the expulsion of lava from beneath the sea under the land, can anyone doubt that he would have discovered and proved the leakage of the oceans, and developed the correct theory of mountain formation?

§ 55. *On the Oscillatory Movements of the Crust Shown in the Coal Measures.*—In view of the results established in this paper we need not dwell on the coal measures, and other evidences of the oscillation of the earth's crust. It suffices to say that these oscillations actually took place, as geologists have long believed. The coal fields in Pennsylvania were formed by vegetation growing rapidly and with great luxuriance over areas near the sea level which were again and again elevated and as often depressed by earthquakes. When the land was under the sea the vegetation died out, and mud and shale were deposited; when the area was again upraised another layer of vegetation was produced, and sometimes it was deposited by floods, currents, and drifting where it had not grown. This was during the Carboniferous Age, and while all the land was near the level of the ocean.

The details of such inquiries must be left to geologists and paleontologists, who study the flora and fauna of past ages. Our aim in these papers has been to give a firm basis for legitimate study and speculation, without which the phenomena of nature remain unintelligible. The progress of the sciences of the earth requires two conditions: first, true physical causes; and second, the intelligent and consistent application of these causes to the explanation of the phenomena, both of the animate and inanimate world. The physicist must content himself with showing the mechanical causes at work and their mode of operation, while the geologist and paleontologist may deal with the evidences of life under these known conditions.

§ 56. *The Equilibrium of the Earth between the Land and Water Hemispheres Explained by the Intumescence of the Land Arising from the Expulsion of Porous Lava from under the Bed of the Sea.* —The remarkable equilibrium preserved by the earth between the land and water hemispheres has long been a matter of speculation among philosophers. Sir John Herschel justly remarked that the high altitude of the continents in the land hemisphere would be most easily accounted for by an intumescence of the land. Pratt has since treated the question in a convincing manner, and shown that the solid parts of the earth's crust beneath the water hemisphere, with pole in New Zealand, must be denser than in the corresponding parts on the opposite side, otherwise the water would flow away towards the land hemisphere and tend to submerge it more completely. (Cf. "Figure of the Earth," 3d edition, pp. 159–160.) Hence he concludes that

"There must therefore be some excess of matter in the solid parts of the earth between the Pacific ocean, and the earth's center which retains the water in its place."

When Pratt wrote this forty years ago there was no suspicion of an intumescent layer beneath the land due to the expulsion of porous lava from beneath the bed of the sea, and accordingly he added that

"This effect may be produced in an infinite variety of ways; and therefore, without data, it is useless to speculate regarding the arrangement of matter which actually exists in the solid parts below."

Now, however, it is proved that the plateaus and continents have been uplifted by intumescent matter expelled from under the sea; and consequently we have data for speculating on how the observed effect is produced.

It is clear that all the great plateaus of the globe and even the continents themselves are underlaid by material lighter than the average of the earth's crust. Naturally the effects are greatest where the plateaus are highest, as in Himalayas and Tibet, where the deficiency in the attraction of these elevated masses long ago attracted attention. In his "Account of the Operations of the Great Trigonometric Survey of India," Calcutta, 1879, General J. T. Walker says:

"There appears to be no escape form the conclusion that there is a more or less marked negative variation of gravity over the whole of the Indian continent, and that the magnitude of this variation is somehow connected with the height.

"Pratt's calculations had reference only to the visible mountain and oceanic masses and their attractive influences—the former positive, the latter negative—in a horizontal direction; he had no data for investigating the density of the crust of the earth below either the mountains on the one hand, or the bed of ocean on the other. The pendulum observations furnished the first direct measures of the vertical forces of gravity in different localities which were obtained, and these measures revealed two broad facts regarding the disposition of the invisible matter below; first, that the force of gravity diminishes as the mountains are approached, and is very much less on the summit of the highly elevated Himalayan table-lands than can be accounted for otherwise than by a deficiency of matter below; secondly, that it increases as the ocean is approached, and is greater on islands than can be accounted for otherwise than by an excess of matter below. Assuming gravity to be normal (in amount) on coast lines, the mean observed increase at the islands stations was such as to cause a seconds' pendulum to gain three seconds daily, and the mean observed decrease in the interior of the continent would have caused the pendulum to lose 2½ seconds daily at stations averaging 1,200 feet above the sea level, 5 seconds at 3,800 feet, and about 22 seconds at 15,400 feet—the highest elevation reached— in excess of the normal loss of rate due to the height above the sea."

The facts here mentioned by General Walker are recognized in geodesy as applying in different degrees to all the elevated tablelands and mountainous regions of the globe. The physical cause of this deficiency in attraction is now established beyond all doubt, and the intumescence of the land, first suggested by Sir John Herschel, is shown to have arisen from the expulsion of lava from beneath the sea. Thus arises the physical condition which secures the equilibrium of the earth between the land and water hemispheres. This must be regarded as not the least remarkable among several interesting results on the physics of the earth deduced from the principle of the secular leakage of the oceans. Earthquakes, volcanoes, mountain formation, the uplift of islands, plat-

FIG. 15. Map Showing the World Ridge. (From Frye's Complete Geography, by permission of Ginn & Co., Publishers.) It will be noticed that the high mountains and great plateaus everywhere face the outside, which is towards the water hemisphere. This map therefore bears impressive testimony to the truth of the New Theory, and the World Ridge stands as an everlasting witness to the secular action of the oceans in uplifting the land hemisphere of the globe.

eaus, and continents, seismic sea waves, trenches and holes in the bottom of the sea, the feeble attraction of mountains, and plateaus, the equilibrium of the globe between the land and water hemispheres, are all closely related and dependent upon a single physical cause.

FIG. 16. Water Hemisphere, which has the World Ridge around it, drawn by W. R. Smith, of Mare Island.

In view of the order and harmony thus established among these varied phenomena, who will not concur in the view of the great Newton that "Nature is pleased with simplicity and affects not the pomp of superfluous causes"?

Conclusions.

Some of the chief conclusions reached in this and the preceding papers on the physics of the earth may be briefly summarized as follows:

1. The theory of the secular leakage of the oceans explains satisfactorily six great classes of phenomena, not heretofore closely associated, namely: (1) Earthquakes, (2) volcanoes, (3) mountain formation, (4) the formation of islands, plateaus and continents, (5) seismic sea waves, (6) the feeble attraction of mountains and plateaus long noticed in geodesy.

2. And the theory not only explains the leading facts of each class of phenomena separately, but also in relation to all the other classes of phenomena; and this harmonious mutual relationship of all the phenomena proves the theory to rest on a true physical cause.

3. A *vera causa,* once established, should not only explain all the phenomena, and all the relations, but also exclude the consideration of other possible causes, by necessary and sufficient conditions. This alone ensures the entire validity of the reasoning, and the present theory meets this severe test perfectly.

4. We have traced the details of the processes involved in mountain formation, and have exhibited illustrations of its working by processes now observed in the depths of the sea. All stages of mountain formation are thus brought out, and they are all shown to be consistent with this simple theory, which explains the principal phenomena of the earth's crust.

5. This theory explains the distribution of mountains about the continents, their great height which the contraction theory cannot account for; the formation of parallel ridges by the uplift of the side of the trough nearest the sea, when the bottom has so far subsided that the folding up of the nearer side becomes the path of least resistance in the expulsion of molten rocks from under the sea.

6. Several successive troughs are often thus dug out, with ridges forced up between them; and when the whole is raised above the water we have a series of parallel ranges, such as the Allegheny, Tuscarora and Blue Ridge Mountains in Pennsylvania and Vir-

ginia. Heretofore these vast billows of the earth's crust have been utterly bewildering to the naturalist.

7. When several such trenches have been dug out, and the expulsion of lava is from both sides, as happens when the sea is thus distributed, the ridges may finally be forced up and so crowded together from both sides that overturned dips and inverted strata are produced, as in the Swiss Alps. No previous theory has been adequate to account for this amazing phenomenon, the explanation of which is thus seen to be exceedingly simple. This test may be justly considered the *experimentum crucis* of the theories of mountain formation.

8. The Andes in South America are nothing but a vast wall or embankment erected by the Pacific Ocean, through the expulsion of lava, along its border. Hence the persistence of the earthquake belt and seismic sea waves along this coast.

9. This embankment includes not only the peaks and chains of mountains, large and small, in the Eastern and Western Cordillera, but also the intervening plateaus, such as those of Quito, Caxamarca, Cuzco, and Titicaca.

10. The molten rock expelled from under the sea is lighter than average material of the layer below the earth's crust, and when the included vapor of steam is allowed to expand, as in volcanoes, pumice is formed, and often blow out in vast quantities. Pumice of various degrees of density underlies the mountain chains, and some of it is blown out of those mountains which become volcanoes.

11. The way in which these plateaus are interwoven with the Andes mountains shows that the whole embankment is due to the continued action of one common cause. And since the mountains were uplifted by the expulsion of lava from under the sea, as proved by the uplifting of the land in earthquakes and the sinking of the sea bottom, indicated by the accompanying seismic sea waves, it follows that the plateaus also are underlaid by matter lighter than the average, which has been expelled from under the ocean.

12. The total quantity of matter thus expelled from beneath the ocean is very large, but it is the result of an infinite number of earthquakes and seismic sea waves during past geological ages. This circumstance affords us an idea of the immense age of the

Andes Mountains, which are the youngest of the great mountain systems of the globe.

13. The terrible fracturing of the crust in the sharp folding involved in the formation of the Andes enabled a vast number of volcanoes to break out, and about one hundred and five have been active within historical times.

14. The formation and activity of the volcanoes in the Aleutian and Japanese Islands is similar to those in the Andes, and represent conditions suitable to the maximum development of volcanic activity. These are sharp folds of the crust near a deep sea from which the expulsion of lava is rapid and violent.

15. The connection of earthquakes with volcanoes and of both phenomena with the sea is clearly established by the geographical distribution and by the vapor of steam emitted by volcanoes. The nature of the underlying material is shown by the ashes, cinders, pumice and lava forced out by the accumulating subterranean steam pressure.

16. Earthquakes, however, are the more general, volcanoes the more special phenomena. The mountains are formed by the sea, but only a few of the peaks break out into volcanoes. No volcano long remains active very far from the ocean or other large body of water, because as the lava hardens in the throat of the volcano the supply of steam is inadequate to maintain activity.

17. If we consider the innumerable islands in the sea, it is evident that they too have been uplifted by earthquakes. Sometimes the sea bottom near them has been undermined in the process of uplifting, and afterwards sunk down, making an adjacent hole in the bottom, and producing seismic sea waves of the first class, as in mountain formation where trenches are being dug out near the continents.

18. Seismic sea waves of the second class are produced by the uplift of the sea bottom, into ridges, or submarine plateaus and islands. In such cases the water rises suddenly without previously withdrawing from the shore.

19. But seismic sea waves of the first class due to the sinking of the sea bottom, after it is undermined by the expulsion of lava, are the most important and most celebrated. The waves at Helike,

373 B. C.; Callao, 1746; Lisbon, 1755; Arica, 1868; Iquique, 1877; Japan, 1896, were all of this class.

20. We may pass directly from the Andes to the Himalayas, and from the high plateaus of South America to those of Asia. Just as the plateaus from Quito to Titicaca were formed by the expulsion of matter from under the Pacific, so also those of Tibet and Iran are due mainly to the expulsion of lava from beneath the Indian and Pacific Oceans.

21. In the case of the plateau of Tibet the resulting uplift is partly due to the combined action of the Pacific, which thus folded the ranges to the East. With two oceans so large and deep as the Indian and Pacific coöperating in this uplift, it is no wonder that the maximum effect was produced and that Tibet became the highest plateau in the world.

22. The Himalayas are higher and further from the sea than the Andes, but the earthquake belt at the base still persists in both cases, and the configuration in regard to the sea shows that the causes at work to produce these mighty uplifts were absolutely similar. And if the mountains are due to the same cause, the plateaus are also.

23. The total height of Tibet is only about one sixth or seventh of the thickness of the earth's crust, and hence the uplift, great as it is, is not such as would necessarily produce great volcanic outbreaks at the surface.

24. Great lava flows, however, occurred in India, and some volcanic phenomenon are known in the Himalayas, but our knowledge of these mountains is not yet adequate to enable one to estimate just how much volcanic activity developed there.

25. Great lava flows are due to the rupture of the crust, by the opening of a fault near the sea, not to volcanic outbreaks. These flows are seen in Utah, Oregon and India, on a scale commensurate with the forces which have uplifted the mountains and plateaus.

26. One may pass directly from the mountains and plateaus of South America to those of Asia, and then to those on the Pacific slope of North America, by the most gradual stages.

27. In this transition the processes are so similar and the differences so small, that it is impossible to deny that the mountains